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DRY TAILINGS DISPOSAL FROM OIL SANDS MINING

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APPENDICES A TO D



IP-19
December 1984

Appendix "A"

"Dry" Tailings Disposal from Oil Sands Mining Coagulation, Stabilization and Water Treatment

Prepared For:

C-H SYNFUELS LTD.

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TABLE OF CONTENTS

	<u>Page No.</u>
1.0 INTRODUCTION	1-1
1.1 SCOPE	1-1
1.2 OBJECTIVES	1-1
2.0 EXPERIMENTAL METHODS	2-1
2.1 SAMPLE PREPARATION	2-1
2.2 PRELIMINARY JAR TEST	2-1
2.3 REGULAR JAR TEST	2-1
2.3.1 APPARATUS	2-1
2.3.2 PROCEDURE	2-2
2.4 COMPACTION TEST (IN JARS)	2-2
2.5 DEWATERING TEST	2-3
2.6 LONG COLUMN TEST	2-3
2.6.1 EQUIPMENT	2-3
2.6.1.1 LONG COLUMN	2-3
2.6.1.2 COAGULATION APPARATUS	2-5
2.6.2 PROCEDURE	2-5
2.6.2.1 SAMPLE PREPARATION	2-5
2.6.2.2 COAGULATION	2-6
2.6.2.3 SETTLING AND COMPACTION	2-6
2.6.2.4 PERMEABILITY	2-6
2.7 ADSORPTION	2-7
2.7.1 ISOTHERMS	2-7
2.7.2 KINETICS	2-8

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
2.8 ANALYTICAL METHODS	2-9
2.8.1 GC/MS	2-9
2.8.2 HEXANE EXTRACTABLES	2-11
2.8.3 CATIONS	2-11
2.8.4 ANIONS	2-12
2.8.5 TOC	2-12
2.8.6 SS	2-12
2.8.7 MOISTURE	2-12
2.8.8 SPECIFIC GRAVITY	2-12
2.8.9 POROSITY AND VOID RATIO	2-13
2.8.10 CATION EXCHANGE CAPACITY	2-14
2.8.11 CONFINED COMPRESSIVE STRENGTH	2-15
2.8.12 POZZOLANIC REACTIVITY	2-15
2.8.13 OTHER ANALYSIS	2-15
2.8.14 TOXICITY	2-16
3.0 RESULTS AND DISCUSSION	3-1
3.1 EXPLORATORY TEST OF COAGULATION OF WHOLE TAR SANDS TAILINGS	3-1
3.1.1 SELF FLOCCULATION	3-1
3.1.2 pH EFFECTS	3-1
3.1.3 LIME ADDITION	3-5
3.1.4 LIME IN COMBINATION WITH FeCl_3	3-7
3.1.5 EFFECT OF POLYELECTROLYTES ALONE	3-7
3.1.6 EFFECT OF LIME AND POLYELECTROLYTE ADDITION	3-8

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
3.2 LIME COAGULATION OF WHOLE TAR SANDS	3-8
3.2.1 INVESTIGATION OF MIXING RATES	3-10
3.2.2 OPTIMIZATION OF LIME DOSAGE	3-10
3.2.3 OPTIMIZATION OF POLYELECTROLYTE DOSAGE	3-12
3.2.4 EFFECT OF TEMPERATURE ON SETTLING	3-19
3.2.5 EFFECT OF RAPID MIX PERIOD ON SETTLING	3-21
3.2.6 SUPERNATANT QUALITY	3-23
3.3 LONG TERM LARGE SCALE SETTLING	3-26
3.3.1 SETTLING AND COMPACTION	3-26
3.3.2 PERMEABILITY	3-32
3.3.3 POROSITY AND VOID FRACTION	3-39
3.4 FATE OF LIME	3-41
3.5 SEDIMENT PROPERTIES	3-45
3.5.1 CURING	3-45
3.5.2 POZZOLANIC REACTIVITY	3-48
3.6 SUPERNATANT TREATABILITY	3-50
3.6.1 COAGULATION	3-53
3.6.2 ACTIVATED CARBON ADSORPTION	3-59
3.6.3 WATER SOFTENING	3-67
3.7 OVERALL PROCESS DESIGN	3-67
4.0 CONCLUSIONS	4-1
5.0 RECOMMENDATIONS	5-1

TABLE OF CONTENTS (CONT'D)

Page No.

ACKNOWLEDGEMENTS

R-1

REFERENCES

R-2

APPENDIX A

A-1

APPENDIX B

B-1

1.0 INTRODUCTION

1.1 Scope

This report is submitted by ZENON Environmental Inc. to C-H Synfuels in fulfillment of a subcontract relating to D.S.S. Contract # RN.KE145-2-0439 "Lime Coagulation and Stabilization of Total Oil Sands Tailings".

This report documents the relevant bench-scale treatability studies on lime coagulation of whole tar sands tailings, examination and testing of the coagulated solids, treatability studies for the associated water treatment systems, and conceptual design of the complete treatment system. An order of magnitude costing for the treatment system is provided in Appendix B.

1.2 Objectives

1. To determine the optimum lime dosage and coagulation conditions for whole tar sands tailings.
2. To determine the settling and compaction characteristics of the coagulated solids, relative to untreated tailings.
3. To determine the fate of the lime, extent of pozzolanic reactions and chemical nature of the coagulated product.
4. To determine the optimum treatment scheme to permit recycle of coagulation supernatant water to process, discharge to surface water or re-use in steam generation for tertiary oil recovery.

2.0 EXPERIMENTAL METHODS

2.1 Sample Preparation

The whole tar sands tailings were received in five-gallon pails. The samples were allowed to stand for a week and then the liquid was decanted. The volume of the solids and liquid was determined. The solids and liquid were recombined for each experiment in proportions noted under "Procedures".

2.2 Preliminary Jar Tests

500 mLs of sample was poured into six 1 L beakers, and each placed under the Phipps and Bird sixplace stirrer (normal jar test stirrer).

The sample was rapid stirred for 30 minutes at 100 RPM and slow stirred (flocculated) for 5 minutes at 20 RPM. Lime and pH control chemicals were added at time zero. FeCl_3 was added, when used, after 25 minutes in the rapid stir mode, and polyelectrolytes, when used, after 29 minutes. Quiescent settling began with the stirrer shutdown. The beakers were removed from under the stirrer and allowed to settle undisturbed.

The position of the interface between the sludge and the supernatant was monitored at different elapsed times.

2.3 Normal Jar Tests

2.3.1 Apparatus

The jar tests were carried out in 1.5 L square battery jars. The jars were stirred with the Phipps and Bird sixplace ganged stirrer.

2.3.2 Procedure

In each jar the solid and liquid portion of the whole tar sands tailings were recombined to represent the original sample. The total volume was 1 L. The standardized procedure used was as follows:

- i) Weigh out CaO, add enough water to form a slurry and stand for 5 minutes. A typical slurry concentration for laboratory work is 25 - 30% by weight of CaO (wet basis).
- ii) Start and set mixer to a setting that will suspend the sand. Mix for about 5 minutes and then pour in the lime slurry. Take care not to trap the lime in the oil.
- iii) Fill a syringe with polymer solution. One mL solution contains 0.5 mg polymer.
- iv) Assuming that the mixing period is 30 minutes, add the polymer at 29.5 minutes, or 30 seconds prior to the end of mixing.
- v) At the end of the mixing period (i.e. 30 minutes), turn off mixer and remove it immediately.
- vi) Allow quiescent settling for the desired period.
- vii) During the settling period monitor the interface height between the liquid and solids.

2.4 Compaction Test (in jars)

After 24 hours the supernatant was carefully removed for analysis, the moisture content of the sludge was determined

and another portion of the sludge was used for dewatering tests. The balance of the sludge was allowed to further compact (correction was made for the sludge removed). The beakers were covered with Parafilm to prevent evaporation.

2.5 Dewatering Test

About a 50 mL portion of each selected sludge was placed into a funnel lined with a folded paper filter (Whatman #1) and was allowed to drain under gravity. A graduated cylinder was placed under the funnel to monitor the water coming from the sludge versus elapsed time. The entire system was covered with a plastic sheet to prevent evaporation. After 48 hours, the moisture content of the sludge was determined.

2.6 Long Column Test

2.6.1 Equipment

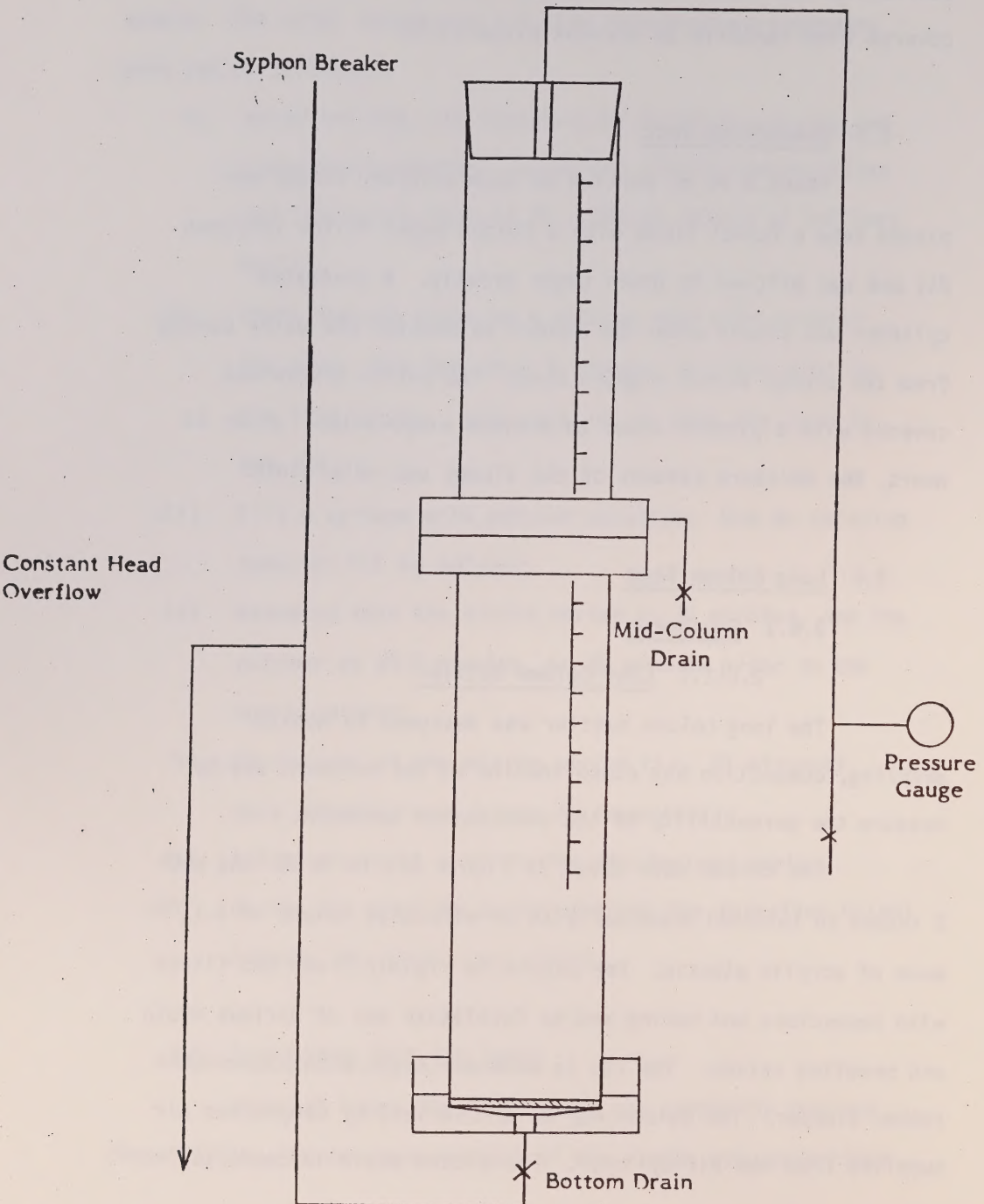
2.6.1.1 Long Column Settler

The long column settler was designed to monitor settling, compaction and consolidation of the sediment and to measure the permeability of the undisturbed sediment.

The column used shown in Figure 2-1 is 10 ft long and 2 inches in internal diameter with an effective volume of 6 L, made of acrylic plastic. The column is rigidly fixed and fitted with connectors and tubing and to facilitate use of various drain and sampling valves. The top is made air tight with a removable rubber stopper. The column may be pressurized by compressed air supplied from the air cylinder. The bottom drain is connected to

FIGURE 2 - 1

SCHEMATIC OF LONG COLUMN SETTLER



a sample collection line, which has a syphon breaker. During permeability tests the syphon break is positioned at the sediment-liquid interface. A measuring tape is fixed to the column along the length.

2.6.1.2 Coagulation Apparatus

The Phipps and Bird sixplace stirrer and the standard battery jars were used to coagulate the whole tar sands tailings sample. The coagulation procedure was carried out on top of a 10 ft scaffolding to allow easy and quick access to the top of the column for filling.

2.6.2 Procedure

2.6.2.1 Sample Preparation

Two lots of tailings samples were used for the column settling tests. The first sample was taken from the same containers used for the third set of jar tests. This 5 gallon sample was allowed to settle and the liquid was decanted. The volumes of the liquid and solid portions were measured to allow representative recombination in the jars.

The second tailings sample was received in eight 5 gallon containers. These samples were allowed to settle and then were decanted. The liquid portions were placed in a 45 gallon drum and the solid portions in a separate 45 gallon drum to eliminate the variations inherent with small samples. Half of the volume of this sample was made up of solids. To bring this sample in line with the previous samples an amount of tap water

was added to the liquid portion to reduce the volume of the solids to 1/3 of the whole sample.

The liquid and solid portions were combined in the jars and the whole sample was warmed to 69°C. The jars were then quickly moved to the mixer.

2.6.2.2 Coagulation

Five sets of runs were conducted with the column settler. Two sets were conducted with 900 mg/l CaO and to one of these 8 mg/L A-110 polyelectrolyte was added.

The stirrer was operated at 150 RPM and the mixing period was 30 minutes. The lime was added at the start of the stirring period and polyelectrolyte 0.5 minutes before the end. Immediately after the stirrer shut down, before any settling occurred, the contents of the jars were poured into the long column.

2.6.2.3 Settling and Compaction

At the start of the long column tests the drain and sample valves were closed and the vent valve was open. As soon as the column was filled, the rubber stopper was secured onto the top of the column.

The position of the interface between the supernatant and sediment was monitored versus elapsed time commencing immediately after filling the column. The interface height was monitored until virtually no day to day change was observed.

2.6.2.4 Permeability

At the end of the sediment compaction the syphon breaker of the sample tube was positioned at the interface to

eliminate the suction caused by draining the column. At this time the drain valve was also opened. The position of the interface and of the liquid level were monitored. The flowrate was measured periodically with a graduated cylinder and stop-watch.

When change in the interface position was no longer observed the vent valve was closed, the column was pressurized to 5 psi and the above procedure was repeated. The column was further pressurized to 10 and 15 psi and interface height, liquid level and flowrate was monitored as above. The column was kept pressurized to 15 psi until the flow rate became constant.

The permeability coefficient K was determined from the interface height, liquid level, pressure and flowrates measured and the following equation:

$$K = \frac{Q L}{P A}$$

where Q = permeate flowrate - cm/sec

L = sediment bed depth - cm

P = pressure above the sediment - cm H₂O

and A = mass sectional area of the column - cm²

The units of K are cm/sec.

2.7 Adsorption

2.7.1 Isotherms

The capacity of the carbon to adsorb solute from water is determined by running "isotherms".

The "isotherm" test involves the contacting of equal aliquots of supernatant with varying amounts of powdered carbon in an agitated container for 14 days. At the end of this period the carbon is separated from the liquid and the TOC and oil and grease level of the liquid in each container is determined. From this data, the amount of organics adsorbed is calculated by the equation:

$$q = \frac{(C_o - C_e)V}{m}$$

solve q = equilibrium loading - mg TOC/g AC,

C_o = initial TOC concentration - mg/L

C_e = equilibrium TOC concentration - mg/L,

V = volume of solution - L and

m = mass of activated carbon - g.

Loading is plotted against the respective residual concentration. The shape of the plot and level of adsorption varies according to the solutes in the liquid and the activated carbon used.

2.7.2 Kinetics

The rate at which solutes adsorb from water onto carbon is determined by the kinetics test.

The kinetics test involves contacting under agitation, equal aliquots of liquid with equal amounts of granular activated carbon and measuring the residual of organics in the liquid of the containers removed from agitation at various periods of

elapsed time. The reduced residual concentration is plotted against the corresponding elapsed time.

The isotherm and kinetics data are combined to facilitate activated carbon contactor design using numerical methods.

2.8 Analytical Methods

2.8.1 GC/MS

i) EXTRACTION

One litre of the treated water was accurately measured into a volumetric cylinder and transferred to a 2 L separatory funnel. 50 mL of CH_2Cl_2 was used to rinse the container and was added to the funnel. The pH of the aqueous portion was adjusted to <1 with conc HCL at which point an additional 100 mL of CH_2Cl_2 was added. The sample was vigorously shaken for 1.5 minutes with regular venting. The extract was drained into a 500 mL round bottom flask and the extraction repeated twice with similar volumes. The combined extracts were rotary evaporated, with solvent exchange to iso-octane then extracts were reduced to a 5 mL final volume in a centrifuge tube and extracted with 2 mL of 0.1 N KOH. At this point, a large quantity of white solid material precipitated necessitating centrifugation (at 2000 R.P.M. for 10 minutes) to separate the phases. Following phase separation, the organic layer was removed and the pH of the aqueous portion adjusted to approximately 8. The aqueous portion was evaporated by blowing with a gentle stream of N_2 at 50°C . 2.0 mL of previously prepared saturated dry HCL in methanol was

added to the sample in a reacti-vial, sealed and heated at 60° for 3 hours to react organic carboxylic acids to the corresponding methyl esters and phenolics to the methyl ethers. After cooling, 1.0 mL of hexane was shaken with the methanol to extract the reacted organics and analysed by GC/MS.

Since such a large quantity of precipitate was formed, there was concern that not all of it would react. For this reason, another subsample was re-extracted as before and left as the free acid in the organic extract i.e. no alkaline extraction was performed or derivatization attempted. This sample was injected directly and was also used for hydrocarbon analysis.

Quantitation of hydrocarbons was performed on the total area of m/z 99 in the sample externally standardized to n-C₁₄H₃₀. Organic acid quantities were estimated from a standard of EPA base/neutral/acid compounds with quantitation on m/z 95.

ii) GC/MS CONDITIONS

Gas Chromatography

Injection Port	- 250°
Injection Mode	- Splitless, 30 sec.
Split	- 30 mL/min.
Septum Sweep	- 4 mL/min.
Column flow	- He @ 20 cm/sec.
Oven Temperature Profile	
800 - 2 min. --	
800 -- 2700 @ 100/min. hold 15 min.	

GC/MS Interface - Direct Couple

Transfer Area - 270°

Mass Spectrometry

Ionization Mode	- Electron Impact
Electron energy	- 70ev
Filament Emission	- 0.5A
Electron Multiplier	- 1100V @ 1×10^6 Gain
Ionizer Temperature	- 170°
Scan	- 90-550 a.m.u. @ .95S-.05S - Bottom Hold

2.8.2 Hexane Extractables

500 mL aliquots of aqueous sample were extracted. The pH of the sample was raised above 12 and the liquid was extracted three times with 50 mL (total 150 mL) hexane in a separatory funnel. The pH of the sample was then lowered below two and extracted three times with 50 mL (total 150 mL) hexane in a separatory funnel. The extracts were then combined and dried over Na_2SO_4 . The dry extracts were evaporated and the residue weighed.

2.8.3 Cation Analysis

The determination of metals was done with inductively coupled plasma (ICP), when the levels of a large number of elements were of interest, and by conventional atomic absorption

(AA) spectrometer when the levels of a single or a few elements were of interest.

2.8.4 Anion Analysis

The aqueous samples were scanned by ion chromatography (IC) for groups of anions; individual anions were determined according to "Standard Methods."

2.8.5 Total Organic Carbon (TOC)

TOC determinations were done with the Beckman Model 915 Carbon Analyzer.

2.8.6 Suspended Solids

Suspended solids were determined according to "Standard Methods".

2.8.7 Moisture Content

An amount of wet sample was weighed and then dried at 69°C overnight. The dried sample was weighed. The moisture content is calculated by:

$$\% \text{ moisture} = \frac{\text{Weight Wet} - \text{Weight Dry}}{\text{Weight Wet}} \times 100$$

2.8.8 Specific Gravity

A weighed amount of dry sample was placed into a 50 mL volumetric flask. Then the flask was filled with water to the mark and weighed.

The weight of 100 mL water was previously determined.
The specific gravity s.g. was calculated by:

$$\text{s.g.} = \frac{W_s}{W_s + (W_w - W_t)}$$

where: W_s = weight of dry solid - g,
 W_w = weight of 100 mL water - g
 and W_t = weight of solids and water - g

The specific gravity may be converted to the value based on water at 40°C by:

$$\text{S.G.}_{40^\circ\text{C}} = \text{S.G.}_{T_i} \cdot \frac{\rho_{C_{T_i}}}{\rho_{C_{40^\circ\text{C}}}}$$

where S.G._{T_i} = specific gravity at ambient temperature,

$\rho_{C_{T_i}}$ = density of water at ambient temperature - g/cc,

and $\rho_{C_{40^\circ\text{C}}}$ = density of water at 40°C
 = 1.0 g/cc

2.8.9 Porosity and Void Ratio

The moisture content of a portion of saturated sample was determined. The weight lost during drying represents the water in voids in the pores of the sample.

The porosity is calculated by

$$\text{Porosity} = \frac{V_w}{V}$$

where V_w = volume of water

and V = volume of water + volume of solids

The void fraction is calculated by

$$\text{Void Fraction} = \frac{V_w}{V_s}$$

where V_s = volume of solids = $\frac{\text{weight of dry solids}}{\text{specific gravity}}$

V_w = volume of water

2.8.10 Cation Exchange Capacity

The determination of cation exchange capacity followed Hesse (1971).

Briefly, 5g of dry sediment was contacted five times with 30 mL sodium acetate. After each contact, the suspension was centrifuged and the liquid discarded. The solids then were washed four times with 30 mL 95% ethanol. The liquid was discarded. Finally the sediment was extracted with three portions of 30 mL ammonium acetate. The combined extract was analyzed for sodium by atomic adsorption spectrometry.

The cation exchange capacity =

$$\frac{(\text{Concentration of Na in the extract})(\text{Volume of extract})}{\text{weight of solids extracted}}$$

and the unit is meq/g.

2.8.11 Unconfined Compressive Strength

Sediment specimen were moulded in greased acrylic tubes 5 cm in diameter and 5 cm long. After periods of curing the specimens were removed from the moulds and were subjected to compression tests in the UCS apparatus.

The instrument provides readings in units of force. The force measurement is divided by the specimen horizontal cross sectional area and then converted to kg/cm².

2.8.12 Pozzolanic Reactivity

Sediment specimens were prepared by adding various amounts of lime (CaO) to dried sediment resulting from coagulation of whole tar sands tailings. Enough tap water was added to the mixture to produce flow to 110% of original specimen diameter. The specimens were moulded in greased acrylic tubes 5 cm in diameter and 10 cm long. The moulds were covered with an airtight plastic sheet and stored at 55°C for seven days and longer. After this period the specimens were removed from the molds and unconfined compressive strength was determined as described in Section 2.8.11. The data is presented in units of kg/cm².

2.8.13 Other Analyses

- i) Suspended solids were determined according to Standard Methods.
- ii) pH was measured with a Model PBL pH meter (Sargent-Welsh Scientific Co.).

iii) Turbidity was determined by a Model DRT 1000 Turbidity meter (HF Instruments)

2.8.14 Toxicity

The toxicity of the water was determined with the Beckman Microtox Model 2055 Toxicity Analyzer. The determination followed the Microtox Operating Manual (Beckman Instruments Inc. (1982), Carlsbad, CA.).

3.0 RESULTS AND DISCUSSION

3.1 Exploratory Tests for Coagulation of Whole Tar Sands

Tailings

Twenty-five beaker settling tests were carried out on whole tar sands tailings. The chemicals added and their dosages are listed in Table 3-1 and results of analyses of the most revealing tests are in Table 3-2.

3.1.1 Self Flocculation

A 500 mL aliquot of whole tailings was slow stirred at 20 RPM for 16 hours and settling was then monitored. During mixing no flocculation was observed and over a period of a week the supernatant remained turbid.

3.1.2 pH Effects

The effect of pH on the sedimentation of whole tailings was investigated in runs 1 through 6. Only in tests conducted at pH 4.6 was the supernatant clear (5.4 NTU). At pH 10.5 the supernatant was turbid (64 NTU), and coloured. At pH 4.6 the oil was clumped and floated while at pH 10.5, it formed a slick on top of the liquid while some was clumped on top of the sediment. As shown in Table 2 the sediment in both cases contained 70-80% water. The data seems to indicate a pH effect on supernatant TOC. Presence of colloidal organics is indicated by the color at pH 10.5 (TOC of 130 mg/L), in contrast with the clear supernatant at pH 4.6 (TOC of 19 mg/L). The metals in the supernatant also tend to dissolve at low pH. Aluminum seems to behave differently

TABLE 3 - 1

CHEMICAL DOSAGES USED IN BEAKER SETTLING TESTS

Jar No.	H ₂ SO ₄	NaOH	Lime (CaO)	FeCl ₃	A110	A137	A11 units in mg/L
<u>RAW</u>							
1	X						
2	X						
3	-	-					
4		X					
5		X					
6		X					
7			300				
8			600				
9			800				
10			1000				
11			2000				
12			3000				
13			800	400			
14			800	800			
15			800		6		
16			800			6	
17					6		
18						6	
19			800		.3		
20			800		.6		
21			800		1.5		
22			800		3		
23			800		6		
24			800		12		

TABLE 3-2

Results and Analyses from Selected Jar Tests

<u>Run</u>	<u>Raw</u>	<u>1</u>	<u>6</u>	<u>9</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>	<u>16</u>
<u>Parameters</u>										
Lime Dosage mg/L	-	-	-	800	2000	3000	800	800	800	800
FeCl ₃ dose mg/L	-	-	-	-	-	-	400	800	-	-
A-110 dose mg/L	-	-	-	-	-	-	-	-	6	6 (A-107)
pH	7.7	4.6	10.5	10.55	10.6	11.95	9.1	7.7	11.3	11.1
Settling*	-	.379	.071	.550	.938	.882	.500	.600	1.0	1.0
Supernatant SS mg/L	33283	30	27	22.5	30	37	9.5	14.0	19.5	37
Supernatant TS mg/L	34357	2192	3691	1379	5392	7270	1360	5392	1384	1384
Sludge %wt H ₂ O	72.6	79.1	72.9	76.1	53.8	42.6	44.8	44.0	34.2	36.7
Dewatering **	.333	.542	.160	.339	1.0	.971	.410	1.0	1.0	1.0

* Settling: $\frac{\text{interface height (at t=0 - at t = 60 min)}}{\text{interface height (at t=0 - at final time)}}$

** Dewatering: $\frac{\text{volume collected at t = 60 minutes}}{\text{total volume collected}}$

cont'd

TABLE 3-2

(cont'd)

Results and Analyses from Selected Jar Tests

<u>Run</u>	<u>Raw</u>	<u>1</u>	<u>6</u>	<u>9</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>	<u>16</u>
<u>Parameters</u>										
Dewatered %wt H ₂ O	83.0	70.5	70.9	52.6	31.7	37.9	32.1	33.3	29.7	28.5
<u>Supernatant Quality</u>										
Turbidity NTU	83	5.4	64	6.8	1.6	0.9	6.9	8.8	14	
Conductivity u mho/cm	2610	3730	5440	2610	8500	11550	2720	4080	3380	
Total Hardness mg/L CaCO ₃	32	192	<2	<2	868	1300	24	372	20	
Alkalinity mg/L CaCO ₃	589	0	2309	513	1824	2561	107	108	576	
TOC mg/L	174	19	130	58	34	31	46	72	37	
SiO ₂ mg/L	22	104	42	104	27	13	24	23	98	
Ca mg/L	6	43	3	3	262	442	9	90	8	
Al mg/L	140	2.9	47	3.8	0.6	0.3	0.2	0.3	2.8	
Fe mg/L	12.1	47.4	1.3	0.2	0.1	0.1	0.2	0.1	0.2	

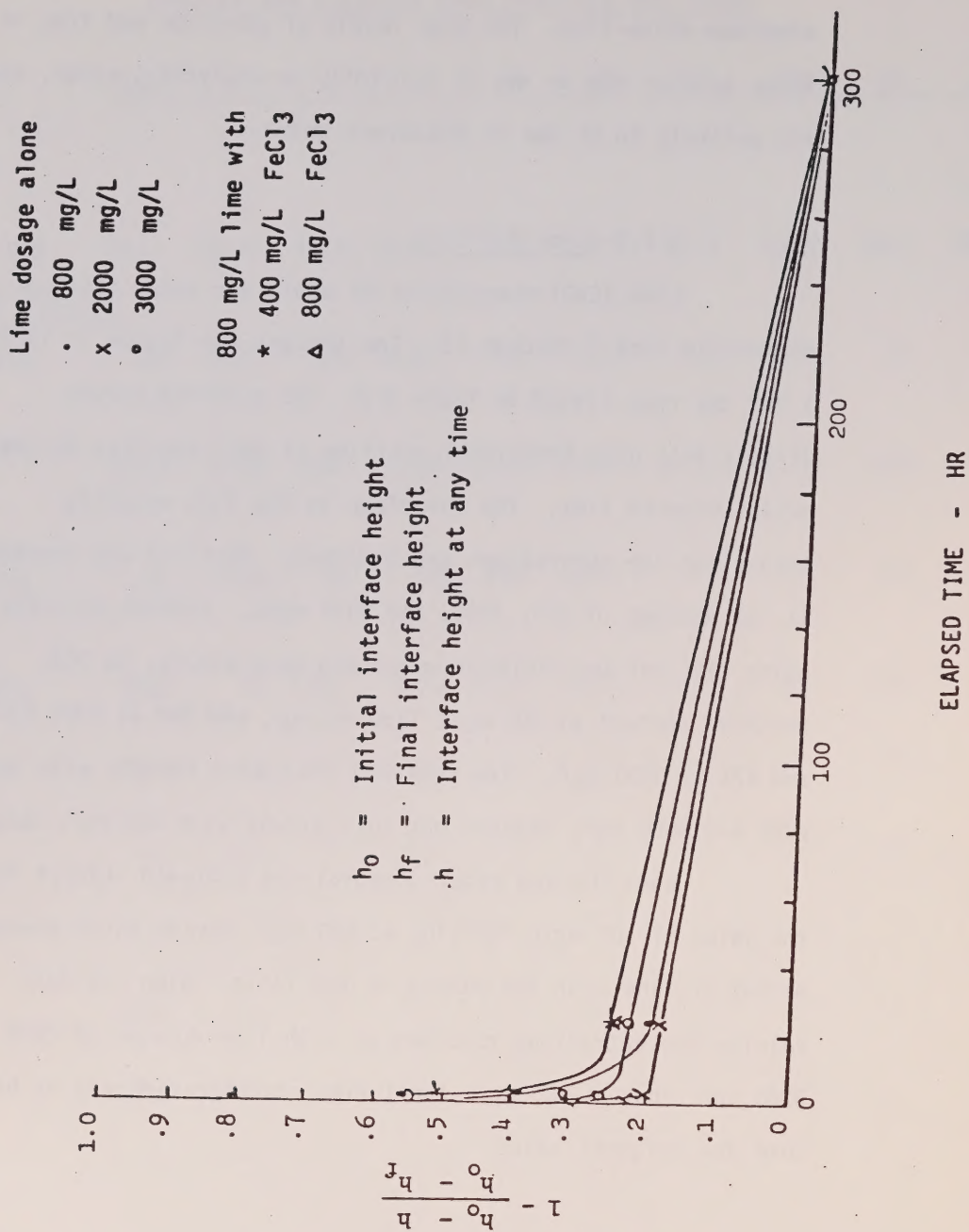
and follow turbidity, thus aluminum must be colloidal and aluminum oxide-like. The high levels of aluminum and iron in three samples may be due to turbidity or analytical error, and are unlikely to be due to dissolved metal.

3.1.3 Lime Addition

Lime (CaO) coagulation of whole tar sands tailings was studied in runs 7 through 12. The dosages are listed in Table 3-1 for the runs listed in Table 3-2. The settling curves (Figure 3-1) plot fractional position of the interface height versus elapsed time. The interface is the line visually separating the supernatant and sediment. Settling was observed at CaO dosages of 800, 2000, and 3000 mg/L. Initial settling was quite fast but the sediment compacted very slowly, to 76% moisture content at 800 mg/L lime dosage, and 54% at 2000 mg/L and 42% at 3000 mg/L. The sediment dewatered rapidly with the 2000 and 3000 mg/L dosages but only slowly with 800 mg/L dosage.

Good TOC and metals removal was achieved, except for the value of 104 mg/L for SiO₂ at 800 mg/L dosage which seems to be out of line with the others in the Table. High residual calcium concentrations resulted at high lime dosages of 2000 and 3000 mg/L, but at 800 mg/L final lime concentration was no higher than the original value.

FIGURE 3-1
SETTLING PROFILE



The surface oil formed a slick on the top with the 800 mg/L lime dosage and clumped and sank to the top of the sediment with the 2000 and 3000 mg/L dosages.

The oven dried sediment appeared hard and brittle and fell apart upon immersion in water.

The 800 mg/L lime dosage was the optimum in this series of tests.

3.1.4 Lime in Combination with FeCl_3

During runs 13 and 14 the addition of 800 mg/L lime was followed by 400 and 800 mg/L FeCl_3 . The settling curves are shown in Figure 3-1 and the analyses in Table 3-2. No appreciable improvement over lime addition alone was achieved and thus no further experiments were carried out with this combination.

3.1.5 Effect of Polyelectrolytes Alone

During runs 17 and 18, 6 mg/L of Cyanamid Magnifloc A-110 and A-137 was added to the whole tar sands tailings. Polyelectrolyte addition at this dosage did not affect the settling. Furthermore, the polyelectrolyte seem to have been trapped in the oil layer, indicating that it would have to be applied under the surface of the tailings. No further experiments were carried out with polyelectrolytes alone.

3.1.6 Effect of Lime and Polyelectrolyte Addition

During runs 15, 16 and 19 through 24, lime and polyelectrolyte addition were combined. Figure 3-2 shows the settling curves with 800 mg/L lime and various dosages of A-110. At dosages of 0.3 mg/L or less the "lime only" curve was reproduced. A drastic improvement in settling was observed with 0.6 mg/L of polymer addition. At 0.6 and 1.5 mg/L dosages the final sediment volume was reached in 10 hours and at 3 mg/L in about 1 hour. Rapid floc formation and settling prior to stirrer shut down was observed. The supernatant was clear for all but the 0.3 mg/L polymer dosage rate. The polyelectrolyte seem to have been trapped in the oil layer when 6 and 12 mg/L dosages were used.

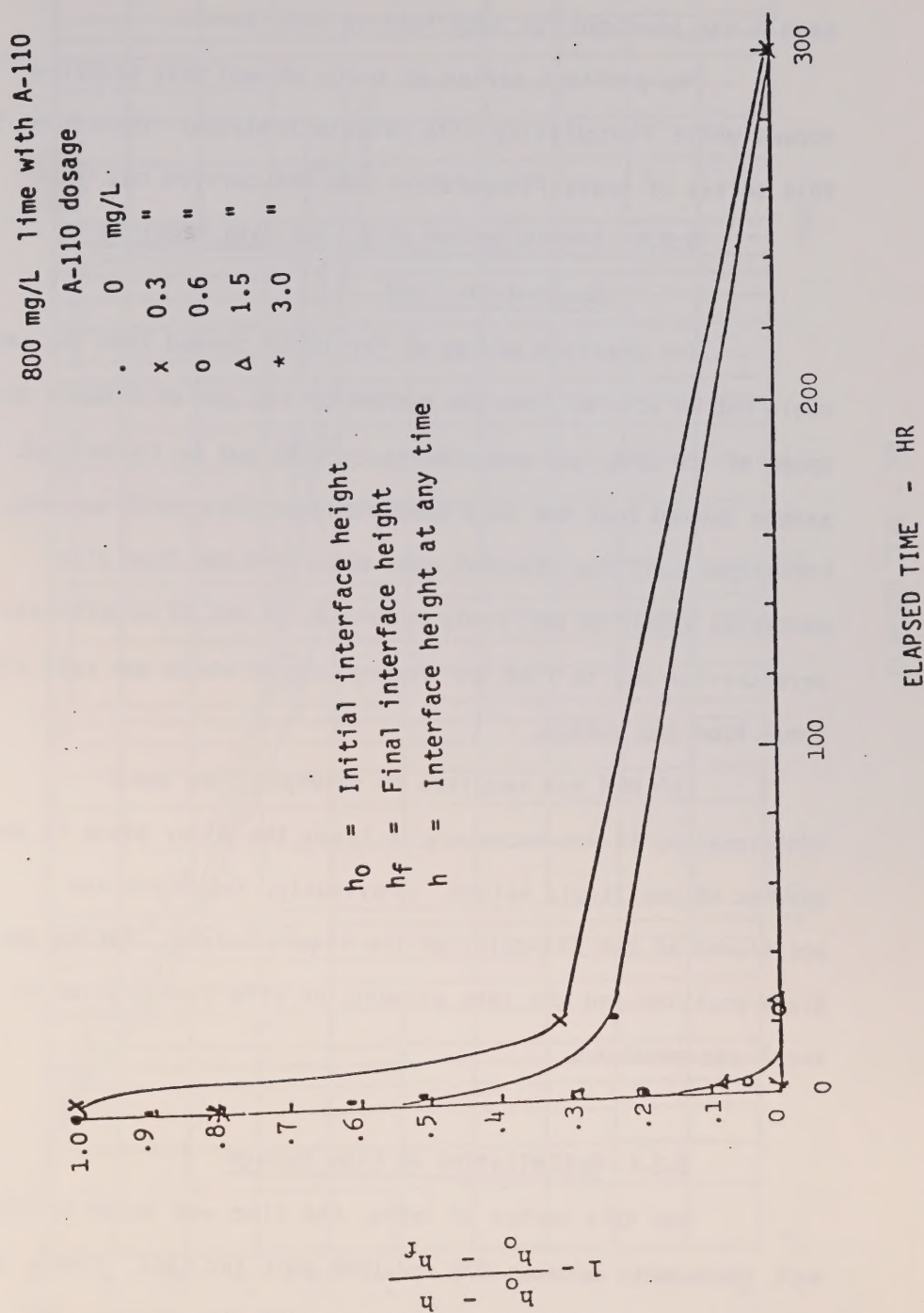
Good TOC and metals removal was achieved as shown for run # 15 in Table 3-2, (except SiO_2) is again high. The oil in all cases was clumped and both floated on top of the water and sank to the sediment-water interface.

The sediment (of runs 15 and 16) contained about 35% moisture and dewatered on a cone filter to about 30% moisture content in one hour. The dried sediment appeared hard and brittle, and fell apart upon immersion in water.

3.2 Lime Coagulation of Whole Tar Sands Tailings

A 5 gallon sample was allowed to settle for five days to separate the sand and other heavier particles from the liquid. Then the supernatant was carefully decanted. This tailings sample contained 33% sand by volume. The liquid and sand were

FIGURE 3-2
SETTLING PROFILE



blended in the correct proportion directly into the jars for the coagulation and settling tests. Thus, a reproducibly uniform sample was provided for each test in this series.

The previous series of tests showed that settling occurs while flocculating with polyelectrolytes. Therefore, in this series of tests flocculation was not carried out.

3.2.1 Investigation of Mixing Rate Required to Suspend the Sand

The previous series of jar tests showed that the sand could not be scoured from the bottom of the jar at a rapid mix speed of 100 RPM, and experiments carried out on the present sample showed that the sand completely settles in 15 seconds. For proper tailings disposal, the sands and the fine clay particles should be uniformly combined. A set of experiments were carried out to find the mixing rate at which the sand will scour from the bottom.

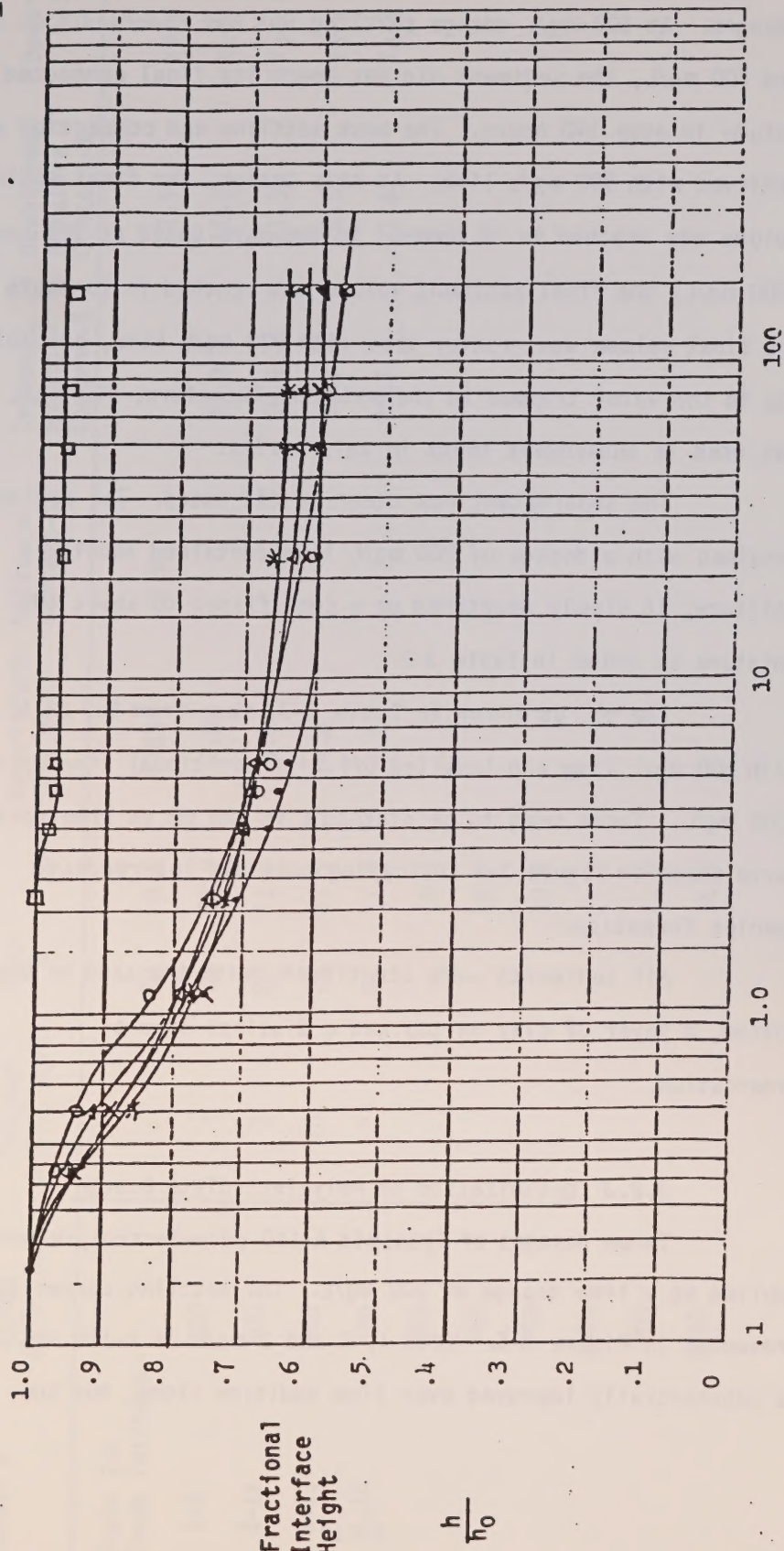
150 RPM was required to resuspend the sand. Additionally, it was necessary to lower the mixer blade to one quarter of the liquid height. Previously, the blade was positioned at the mid-point of the liquid height. Taking the blade position and RPM into account, an effective G value of 340 sec⁻¹ was obtained.

3.2.2 Optimization of Lime Dosage

For this series of tests, the lime was dosed in 100 mg/L increments between 500 and 1000 mg/L (as CaO). Figure 3-3 presents the settling curves obtained with the various lime

FIGURE 3 - 3

EFFECT OF LIME DOSAGE IN SETTLING



ELAPSED TIME - HR.

dosages. At 500 mg/L dosage settling was not observed. At 600 and 700 mg/L, the sediment did not reach its final compacted volume in even 140 hours. The best settling and compaction was achieved with 900 mg/L lime. At this dosage, the final sediment volume was reached in 10 hours. In the jars dosed at 800 and 1000 mg/L, the final sediment volume was reached in 25 hours and the final volume was greater than with 900 mg/L lime, probably due to the water trapped in the matrix. Therefore, 900 mg/L lime was used in subsequent tests in this series.

The supernatant was clear in all cases. The sediment obtained with a dosage of 900 mg/L lime contained about 27% moisture; it slowly dewatered on a cone filter to about 19% moisture as shown in Table 3-3.

The pH, as shown in Table 3-3, rose from 8.3 to 11.3 with 800 mg/L lime and levelled off with additional lime up to 1000 mg/L. There seem to be plateau's in the pH vs lime dosage curve shown in Figure 3-4 indicating possible intermediate species formation.

All sediments were stratified, with the sand on the bottom, a layer of clay on top and a distinct line of demarcation.

3.2.3 Optimization of Polyelectrolyte Dosage

Three dosages of Cyanamid A-110 polyelectrolyte were applied at a lime dosage of 900 mg/L. The settling curves are presented in Figure 3-5. With 1, 2 and 3 mg/L of A-110 settling is substantially improved over lime addition alone, but the

TABLE 3-3

Physical and Chemical Parameters from selected Jar Tests

Sample #	Lime mg/L, CaO	Polymer A-110, mg/L	Temp °C	pH	Supernatant SS - mg/L	Moisture Content-%	Sediment Moisture Content-%	Dewatered Moisture Content-%	Dewater Rate
Whole Tar Sands Tailings	-	-	20	8.3	3785	62.4		22.6	Very Sl
2-5	900	-	20	11.9	7.8		27.3	18.8	Very Sl
2-12	900	3	20	11.9	3.6		28.9	21.3	Fast
2-13	900	10	20	11.9	14.0		35.2	25.8	Very Fa
2-14	900	3	69	11.9	1.2		29.5	21.8	Fast
	500			9.8					
	600			10.7					
	700			10.8					
	800			11.3					
	900			11.9					
	1000			11.9					

FIGURE 3-4

pH AS FUNCTION OF LIME DOSAGE

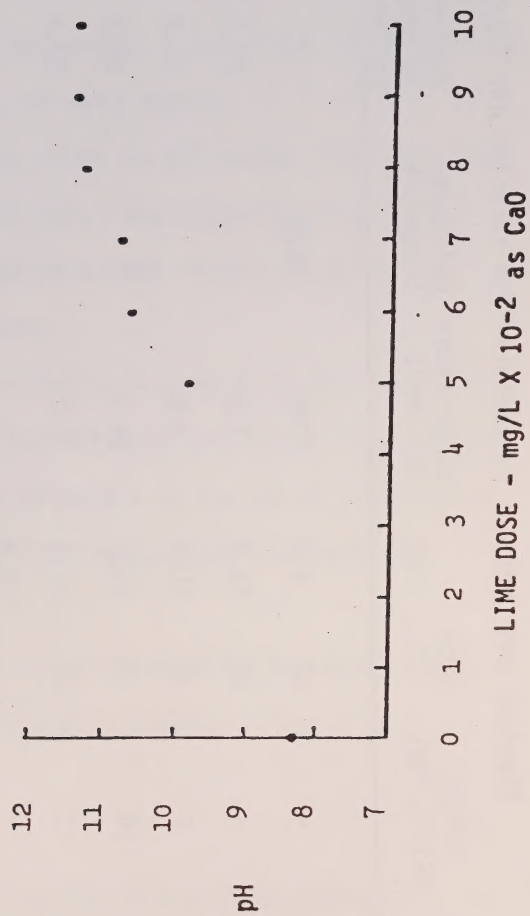


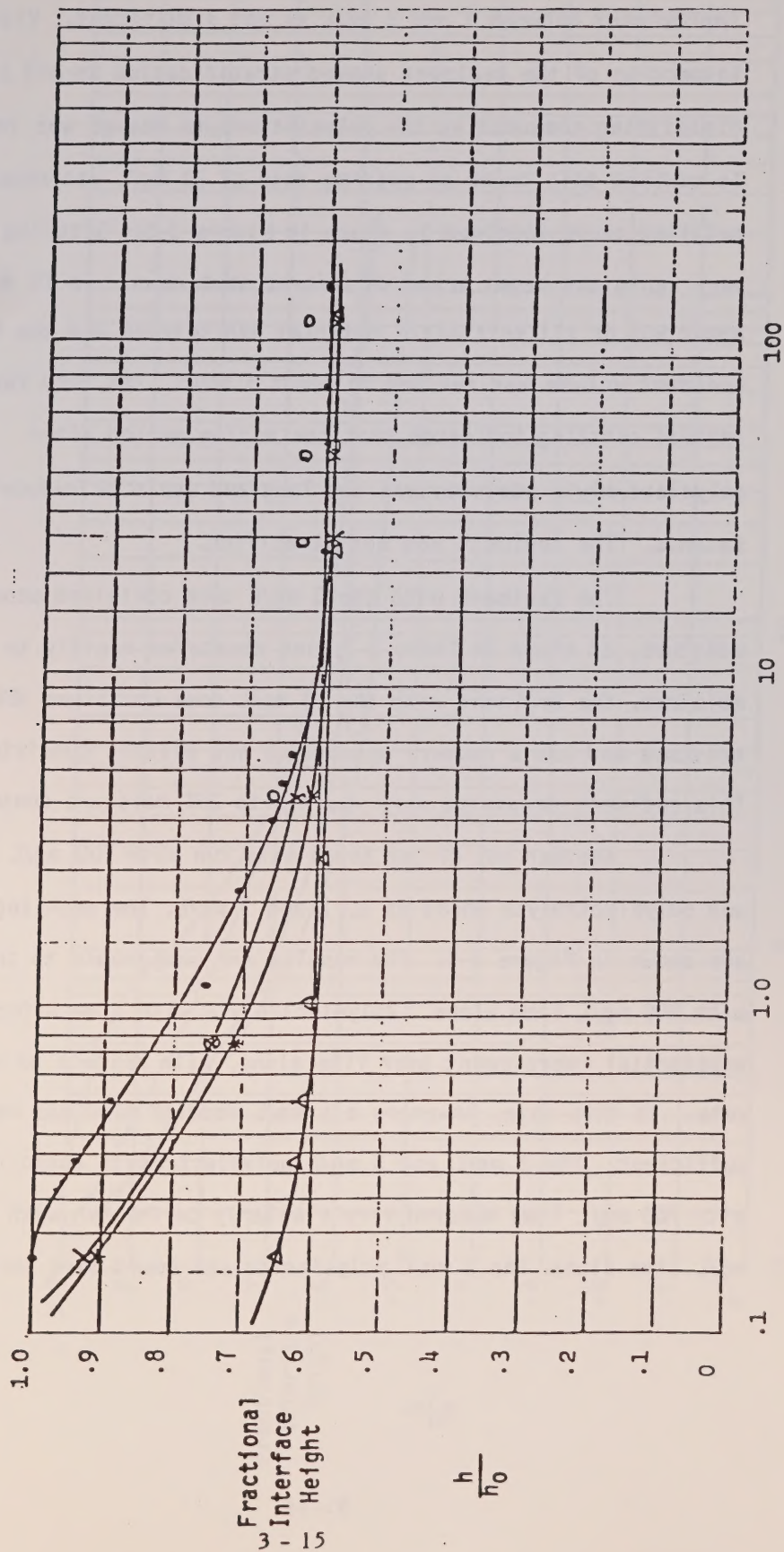
FIGURE 3-5

EFFECT OF POLYELECTROLYTE DOSAGE ON SETTLING

Lime Dose:
900 mg/L as CaO

A-110 dose - mg/L

- 0
- x 1.0
- o 2.0
- * 3.0
- Δ 10.0



improvement between 1 and 3 mg/L is not significant. Visual inspection of the sediment showed stratification in all cases, diminishing somewhat as the polyelectrolyte dosage was increased. To confirm this trend an extreme dose of 10 mg/L was added. The settling curve obtained is shown in Figure 3-5. Settling was very rapid and began prior to stirrer shut down. In 15 minutes, about 90% of all settleable material had settled and the final sediment volume was reached in about 1 hour. The very fast initial settling indicated that the mixing period after polyelectrolyte addition was too long and could be reduced to 30 seconds. The sediment was not stratified.

The sediment with the 3 mg/L dose contained about 29% moisture, as shown in Table 3-3, and dewatered rapidly to 21% moisture. the sediment with the 10 mg/L dose contained 35% moisture and had a rubbery appearance and elastic consistency. This sediment dewatered very rapidly to 25% moisture content.

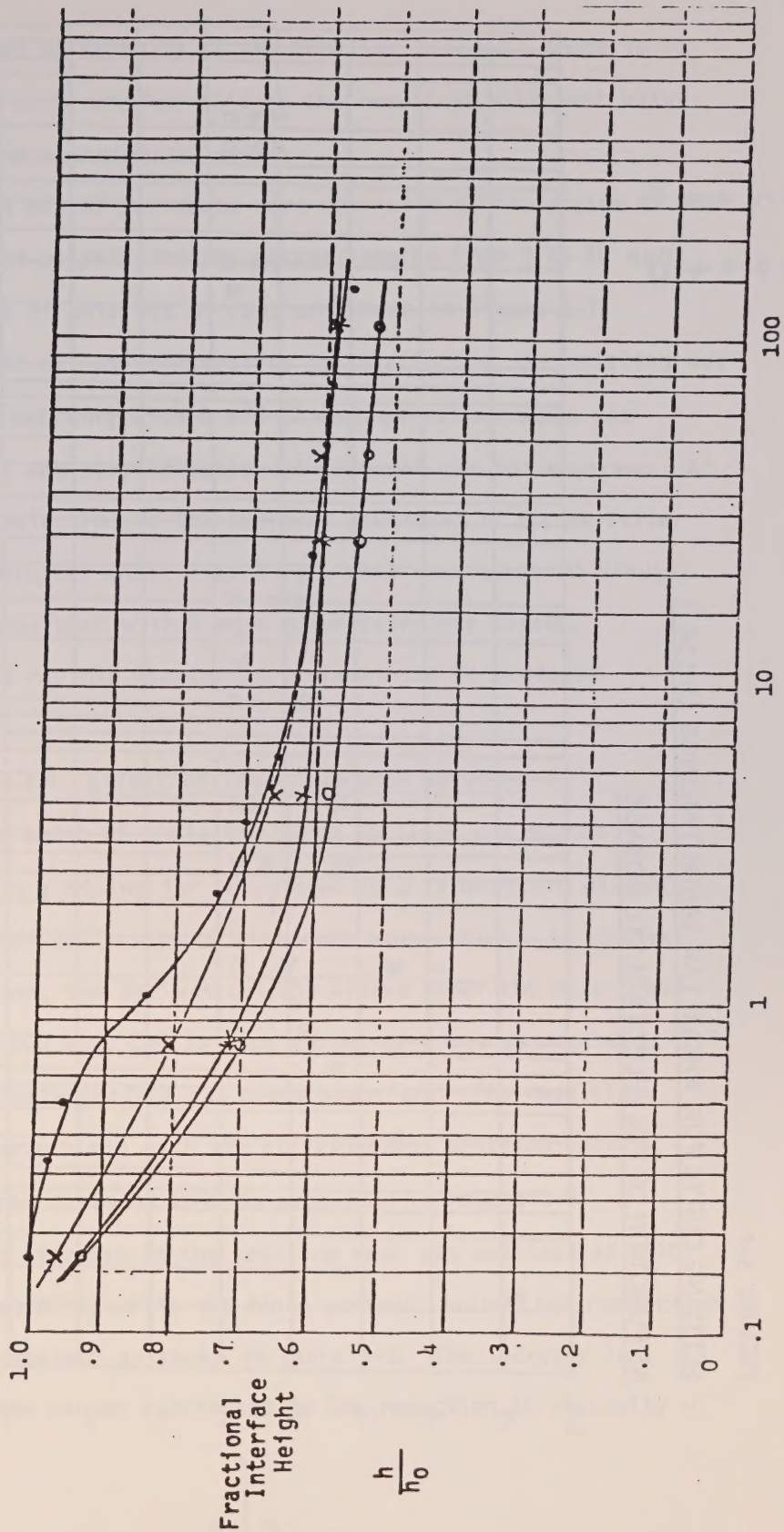
Another set of jar tests were run with 700 mg/L lime and polyelectrolyte doses of 1, 2 and 3 mg/L. The settling curves are shown in Figure 3-6. The results are comparable to the runs with 900 mg/L lime alone. Polyelectrolyte with lime offers substantial improvement over lime alone, with respect to settling rate. In this case, however, a 1 mg/L dose of A110 was not sufficient. The 2 mg/L and 3 mg/L polyelectrolyte dosed runs with 700 mg/L lime behaved very similarly to the run with 900 mg/L lime alone. The 2 mg/L polyelectrolyte dosed jars seem to

FIGURE 3-6

EFFECT OF POLYELECTROLYTE DOSAGE ON SETTLING

Lime Dose:
700 mg/L as CaO

A-110 dose - mg/L
 . 0
 x 1.0
 o 2.0
 + 3.0



ELAPSED TIME - HR.

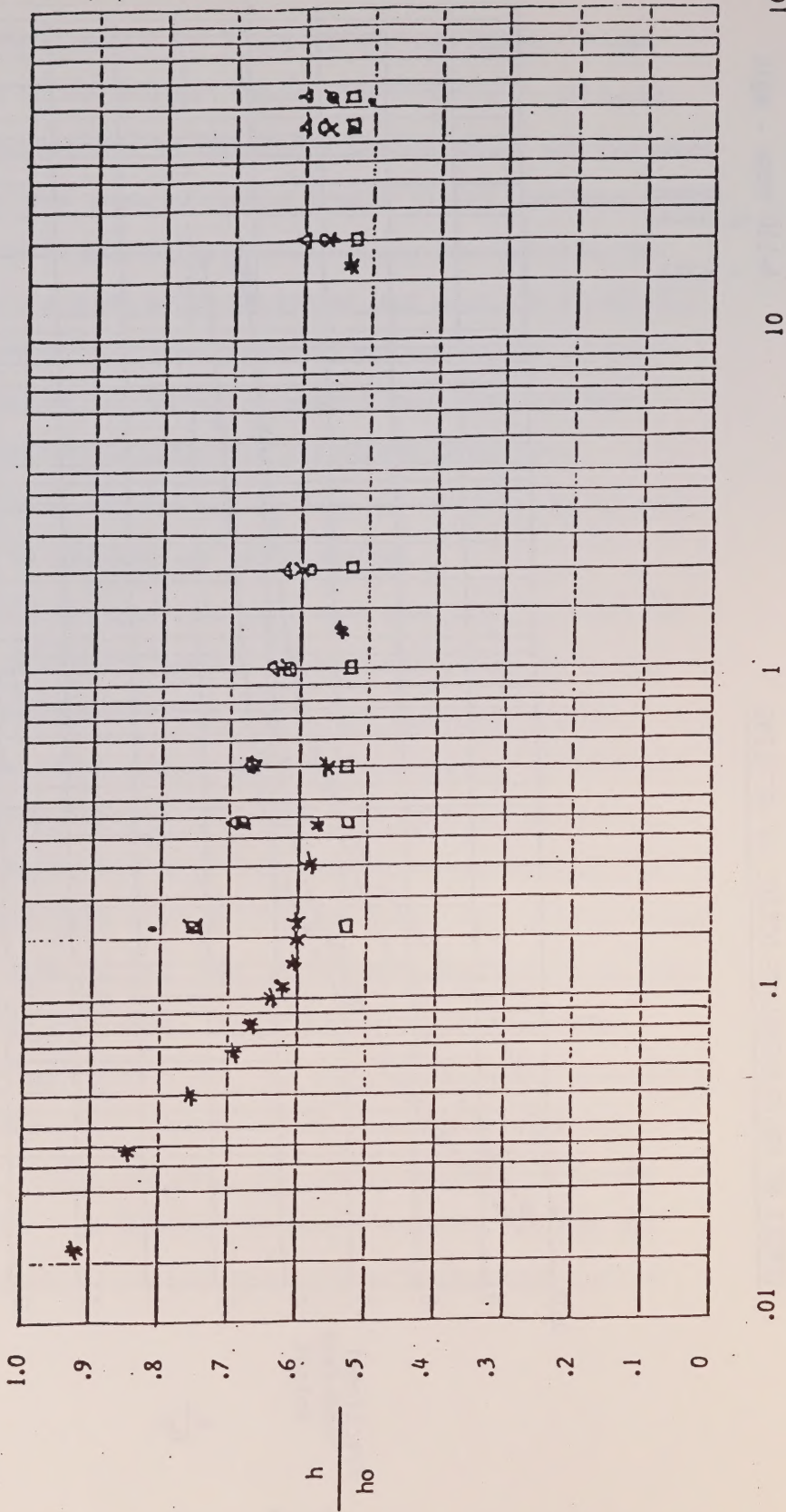
A-110 dose mg/L

- 3
- x 4
- o 5
- Δ 6
- * 8
- 10

FIGURE 3-7

SETTLING CURVE FOR WHOLE TAR SANDS TAILINGS (3rd SET)

AS FUNCTION OF POLYELECTROLYTE DOSAGE



ELAPSED TIME - HR.

have settled differently at the two lime dosages. There is no indication as to whether this is the result of different water chemistry or experimental error.

A set of jar tests were done with a lime dosage of 900 mg/L CaO and polyelectrolyte dosage ranging from 3 to 10 mg/L. The results of this set of runs are shown in Figure 3-7.

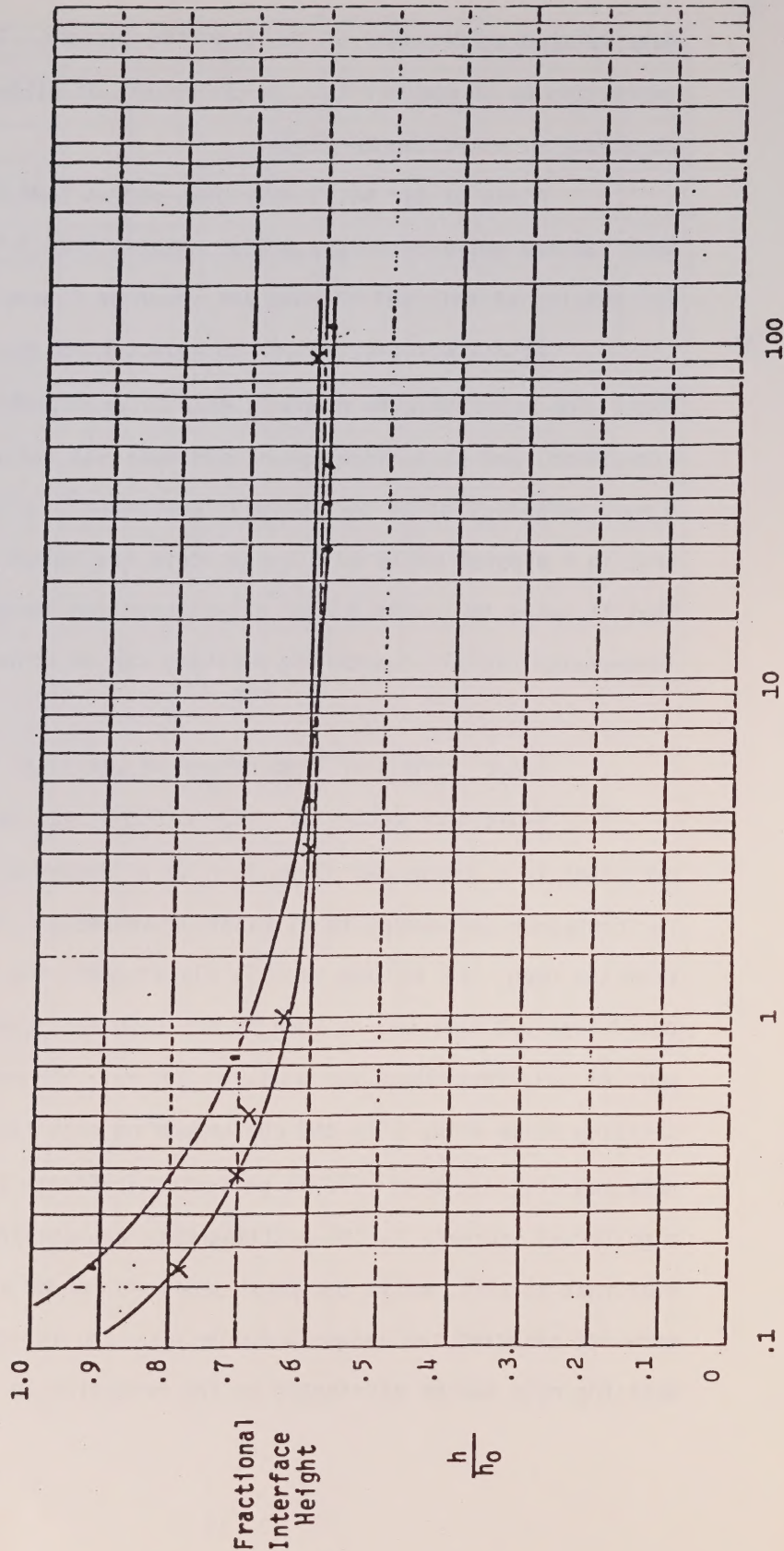
At all polyelectrolyte dosages tested, the settling was fast. The settling with 8 and 10 mg/L polyelectrolyte was exceptional and stratification of sediment was not observed. At 8 mg/L polyelectrolyte the sediment dewatered in a cone filter test in 3 minutes while with 3 mg/L this took about 30 minutes. Thus it seems that with 8 mg/L polyelectrolyte dosage, homogeneous rapidly dewatering sediment can be produced.

3.2.4 Effect of Temperature on Settling

A batch of whole tar sands tailings was heated overnight in a mixing jar in an oven to a temperature of 69°C. The container was sealed to eliminate evaporation. On removal from the oven, the jar was quickly placed under the mixer, and dosed with 900 mg/L CaO as soon as the sand was resuspended. 3 mg/L of polyelectrolyte was added as before. The resulting settling curve along with the corresponding settling curve obtained from a run at 20°C is presented in Figure 3-8. A significant increase in the settling rate was obtained at 69°C over that at 20°C, while the final sediment volume and compaction were not affected, as shown in Table 3-3. The increase in settling rate can be attributed to the reduction in viscosity of

FIGURE 3-8

EFFECT OF TEMPERATURE ON SETTLING



ELAPSED TIME - HR.

the water. At 69°C, the viscosity of water is 40% of the viscosity at 20°C.

The other difference observed at a tailings temperature of 69°C was the appearance of the oil. At 69°C, more oil floated in a slick on the top of the water than at 20°C, and the oil lying on the sediment was formed uniformly in spherical globules about 1/8 inch in diameter. At 20°C, the oil particles lying on the sediment had random shapes and sizes, primarily because viscosity was high enough that the bitumen no longer behaved as a free liquid.

3.2.5 Effect of Rapid Mix Period on Settling

A set of runs with 900 mg/L CaO and 3 mg/L A-110 was conducted to determine what effect the length of the rapid mix period has on settling. The lime was added, as usual, at the start of the rapid mix period and the polyelectrolyte at 1 minute prior to the end of the rapid mix period. The polyelectrolyte was added in these runs to terminate whatever chemical and physical coagulation was occurring and thus demonstrate the effect on settling. Figure 3-9 presents settling curves obtained following rapid mix periods ranging from 2 minutes to 30 minutes. The figure shows that rapid mix periods of 2 and 5 minutes were not satisfactory, as a well compacted sediment was not obtained at two minutes, and slow compaction was obtained at 5 minutes. The curves for rapid mix periods of 10 minutes and longer show some scatter, thus it is difficult to exactly state the best time. For

Lime Dose:

900 mg/L as CaO

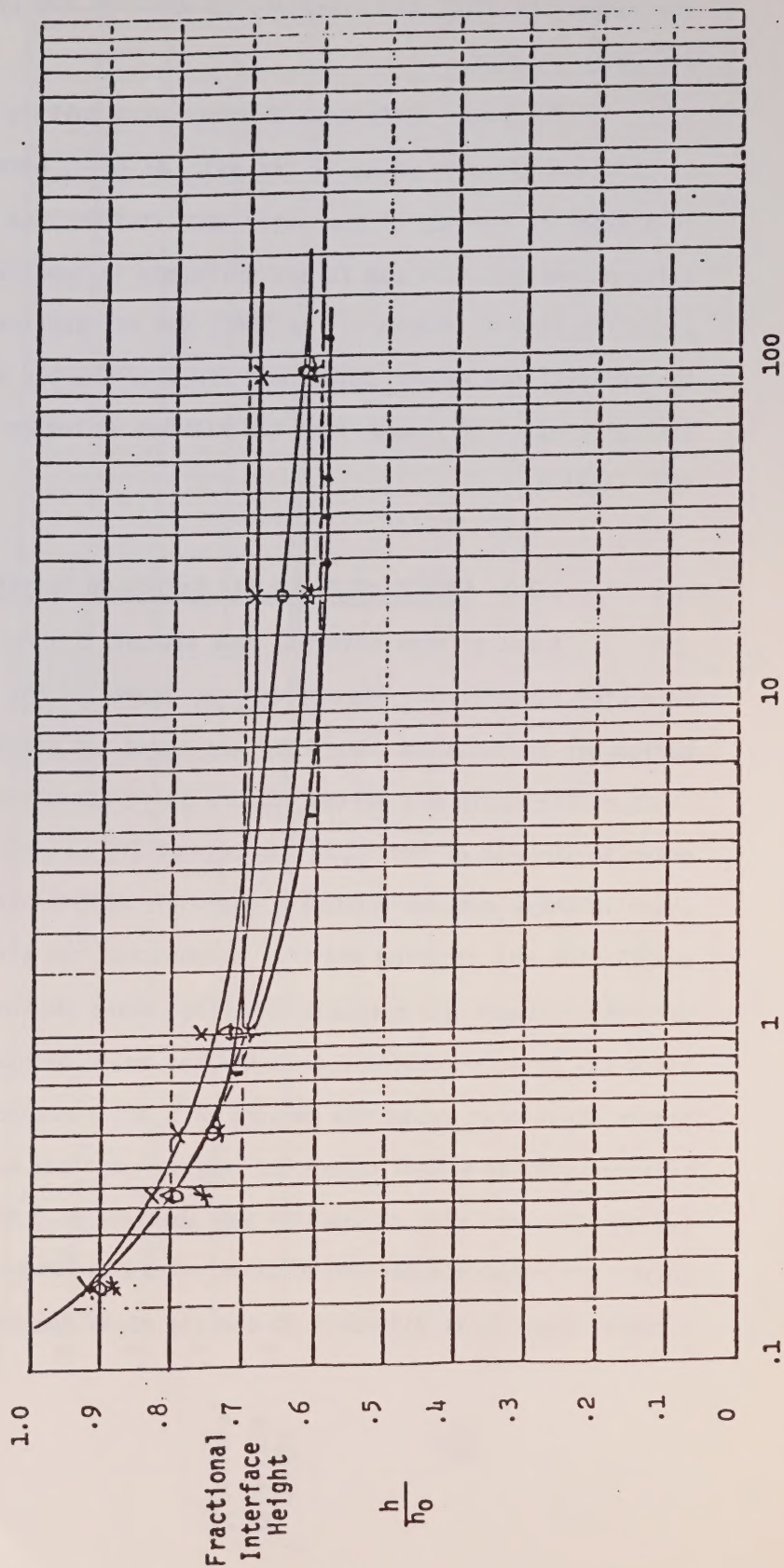
A-110 dose 3 mg/L

Rapid mix period - min.

x 2
o 5
Δ 10
* 20
• 30

FIGURE 3-9

EFFECT OF THE LENGTH OF RAPID MIX PERIOD ON SETTLING



the data presented, a 10 minute rapid mix period seems optimal, considering initial settling characteristics.

The results of a duplicate run are shown in Figure 3-10. Again the data does not show any drastic differences, however, the indications are that the longer the mixture is stirred the more likely it is that a better supernatant quality will be achieved. The improvement in supernatant quality based on turbidity seems to level off after 20 minutes of rapid stirring. The previous set of runs seemed to indicate 10 minutes mix time was sufficient, however, further examination of all the data suggests that a 20 minute rapid mix will yield more reliable results.

3.2.6 Supernatant Quality

The results of chemical analyses done on the second whole tar sands tailings sample and selected supernatants resulting from coagulation are listed in Table 3-4.

Comparison of test results with those from the first series of tests show that most parameters fell into the same range. However, there were also significant differences. Aluminum, iron and TOC concentrations in the raw samples were lower. However, some of the differences could be due to the fact that this time a whole tar sands sample was submitted for analysis versus a supernatant only last time. Silica levels were consistently high in supernatant (144-172 mg/L) and calcium consistently low (1.7 - 7.9 mg/L)

The quality of supernatants obtained was very similar to quality obtained under the same coagulation conditions in the

A-100 dose 3 mg/L
 Rapid mix period - min.
 x 2
 o 5
 o 10
 △ 15
 □ 20
 ▲ 25
 * 30

FIGURE 3-10

SETTLING CURVE FOR WHOLE TAR SANDS (3rd SET)
 AS FUNCTION OF THE RAPID MIX PERIOD

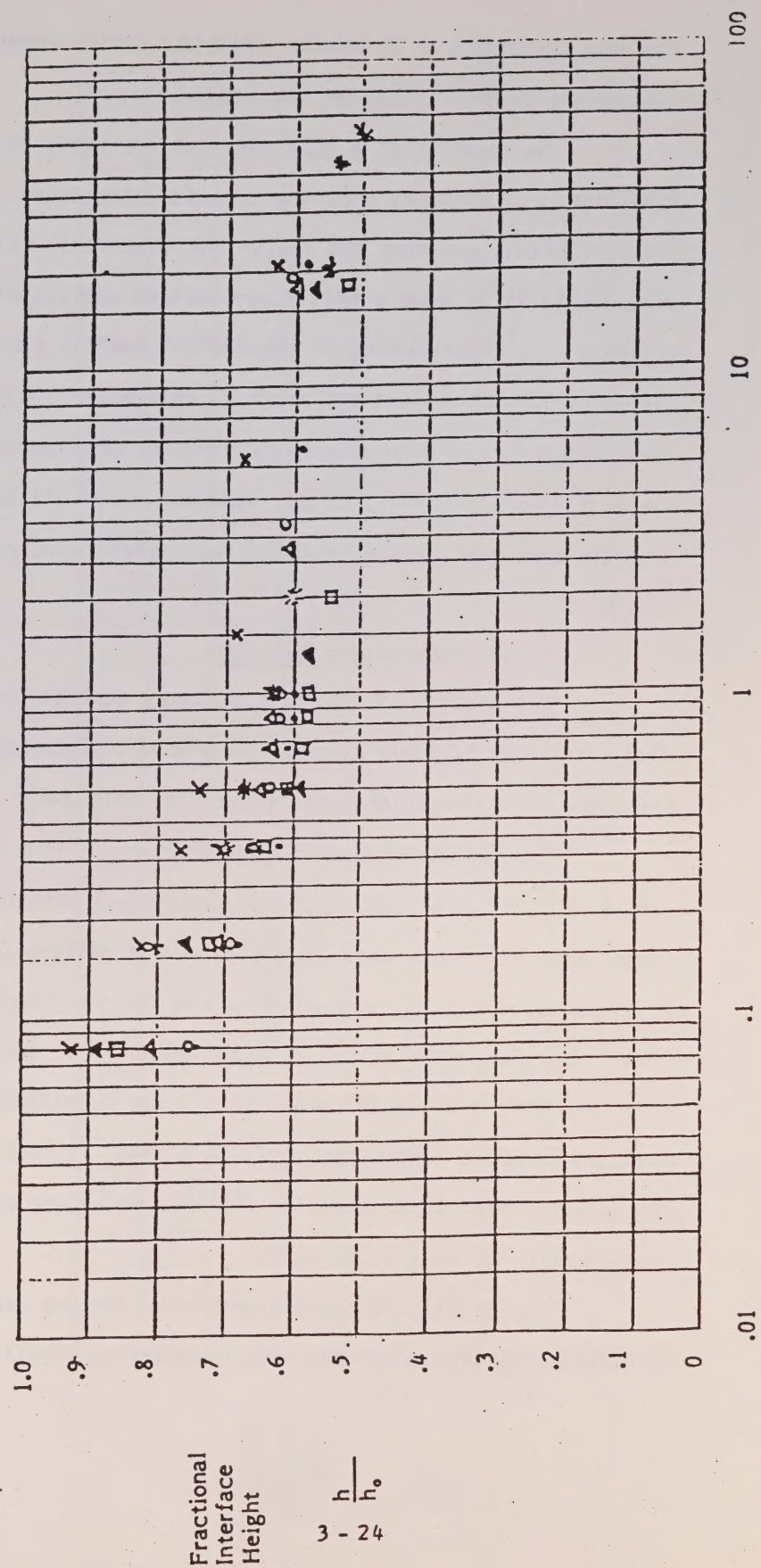


Table 3-4
SUPERNATANT QUALITY

Sample #	whole tar sand tailings	2-5	2-12	2-13	2-14
Parameter					
Turbidity, NTU	---	1.1	0.9	6.0	0.6
Conductivity umho/cm	---	2920	3500	4080	3850
Total Hardness mg/l CaCO ₃	40	5	33	20	55
Total Alkalinity mg/l CaCO ₃	498	633	731	718	766
TOC mg/l	65	68	51	66	76
SiO ₂ mg/l	35	172	153	166	144
Ca mg/l	11.2	1.7	4.0	7.8	7.9
Al mg/l	0.5	0.29	0.38	0.73	0.83
Fe mg/l	0.10	0.06	0.13	0.06	0.16

first series of tests. The TOC level of supernatant following high temperature coagulation (sample 2-12 in Table 3-4) was higher than the value obtained from a comparable coagulation test at room temperature (sample 2-15 in Table 3-2). However, the rise in concentration does not seem very significant.

3.3 Long Term Long Column Settling

While a jar test can correctly determine dosages required for treatment, it is not a suitable method for determining the long term and larger scale effects. The long column settler construction allows the treatment of a larger volume of sample and subjects it to conditions more closely resembling the possible deposition and drainage methods. Separate tests were conducted with whole tar sands tailings, the settleable fraction, lime coagulated whole tar sands tailings and lime coagulated and polyelectrolyte flocculated whole tar sands tailings.

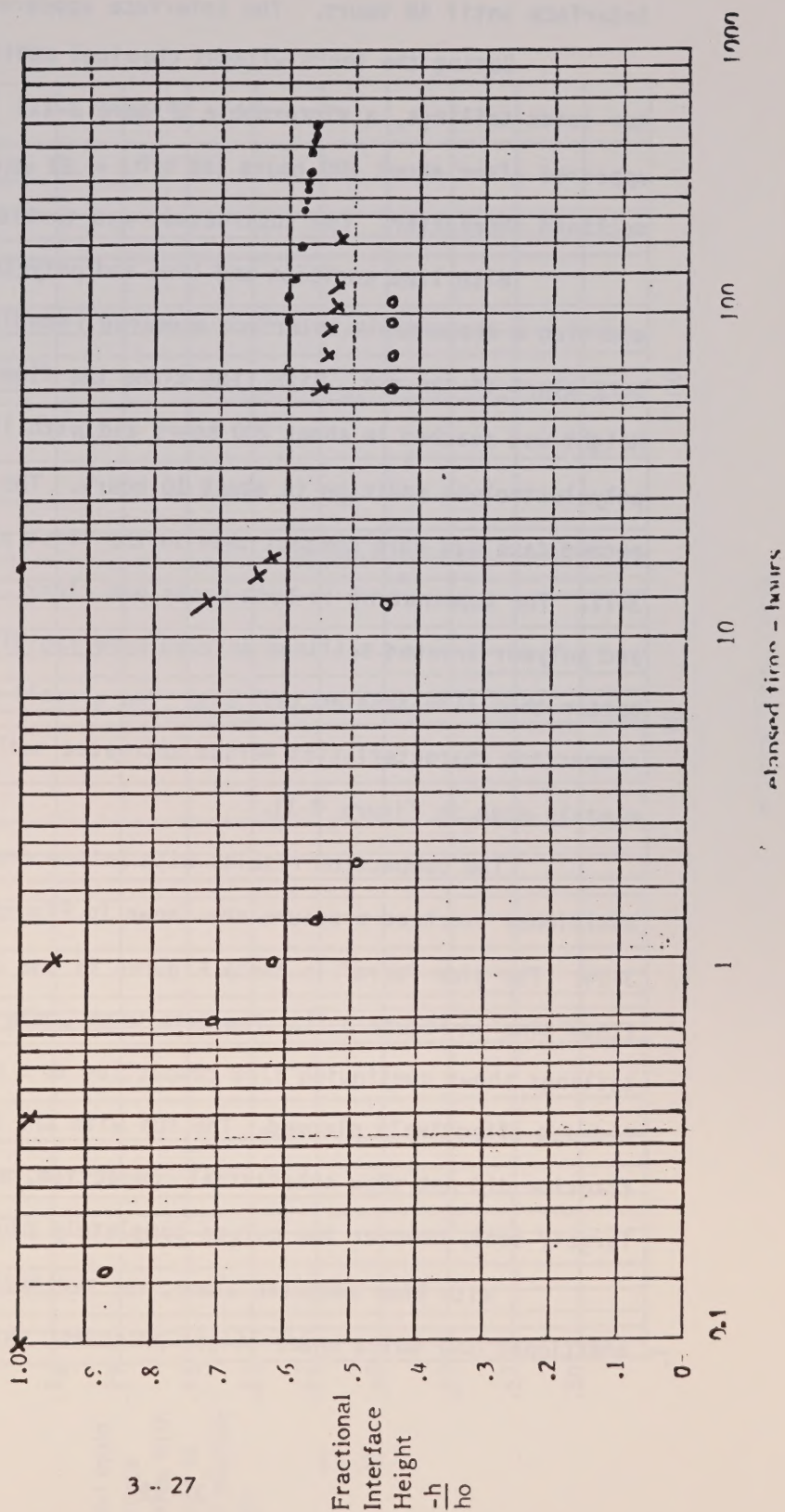
3.3.1 Settling and Compaction

Figure 3-11 presents results of the long column settling tests with and without chemical addition on whole tar sands tailings. An additional run was also carried out on the settleable fraction only of the tar sands tailings (not shown). For this test the settleable fraction which is mostly sand with a small amount of trapped clay was placed into the long column to a $h/h_0 = .6$ (the original sample proportion) and the column was

SETTLING AND COMPACTION OF UNTREATED AND TREATED WHOLE TAR SANDS TAILINGS

Treatment

- none
- x 900 mg/L CaO
- o 900 mg/L CaO & 8 mg/L A-110



filled with tap water. This run did not show any discernable interface until 48 hours. The interface appeared at $h/h_0 = .44$.

During the tests without chemical addition, on whole tar sands tailings, a discernable (Figure 3-11) interface appeared after about 100 hours (at $h/h_0 = .6$) which slowly declined thereafter. The supernatant was turbid.

With lime addition and lime and polyelectrolyte addition a discernable interface appeared immediately, at the very start of the run. With lime alone the final interface height was reached in about 200 hours and with lime and polyelectrolyte addition in about 10 hours. The sediment in the second case was more compact than in the first as shown in Figure 3-11. The supernatant in both cases was clear. Overall the lime and polymer treated tailings settled more rapidly and compacted better than lime-treated tailings. The overall improvement in compaction characteristics versus untreated tailings can be clearly seen in Figure 3-11.

The compaction results with bottom drainage and additional overhead pressure are shown in Figure 3-12, 3-13 and 3-14. The time "zero" in these Figures is the corresponding final time in Figure 3-11. The data with whole tar sands tailings shows continuing slow compaction to a point where the bed was effectively plugged. The run with the settleable fraction did not show substantial compaction, as this fraction is largely sand, however the column completely plugged in 19 hours.

With lime addition alone, the sediment compacted an additional 0.07 units under 15 psi pressure. With the addition

FIGURE 3-12

COMPACTION OF WHOLE TAR SANDS TAILINGS WITH DRAINAGE IN THE LONG COLUMN UNDER PRESSURE

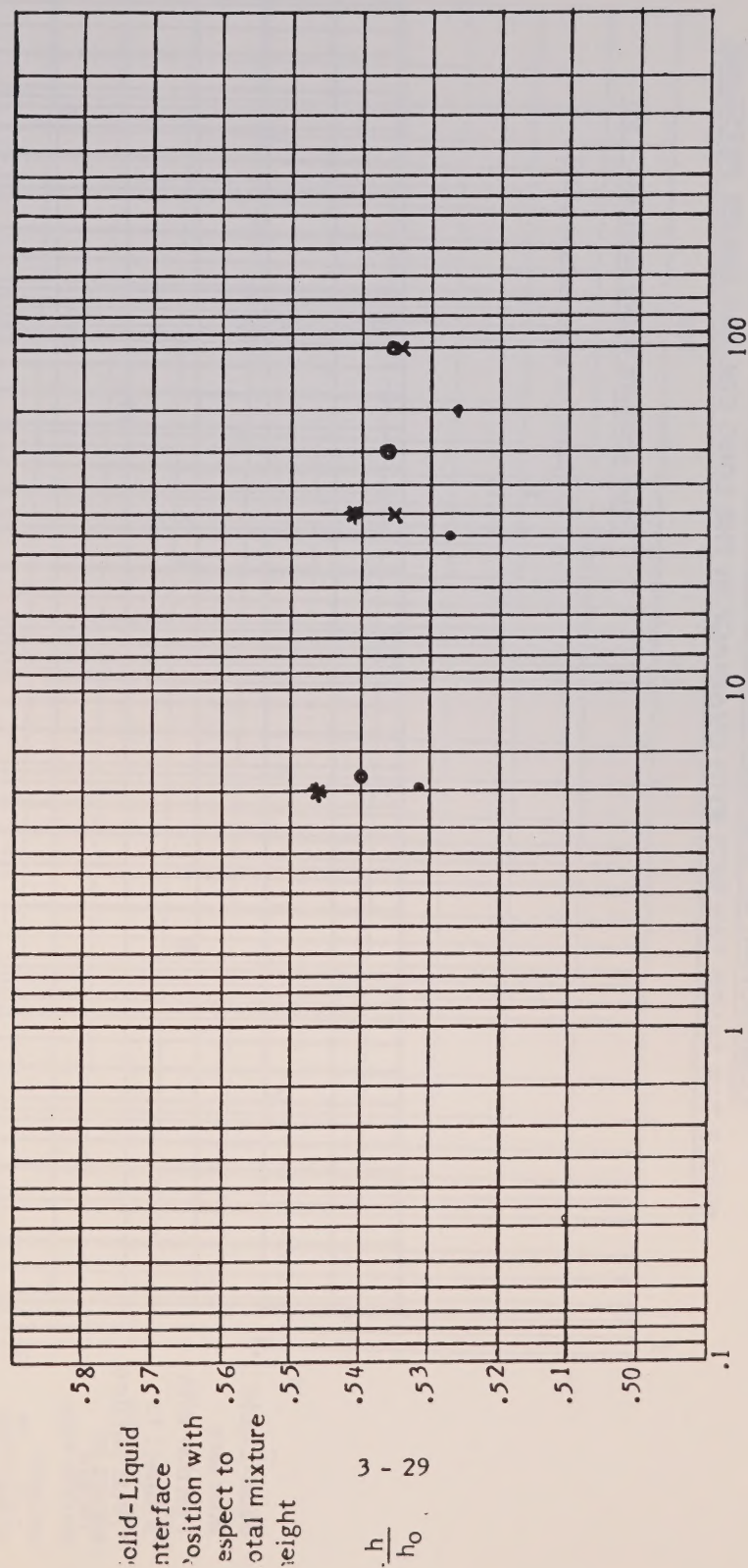
Total pressure above sediment - psi

* 2 (layer of supernatant only)

o 7

x 12

• 17



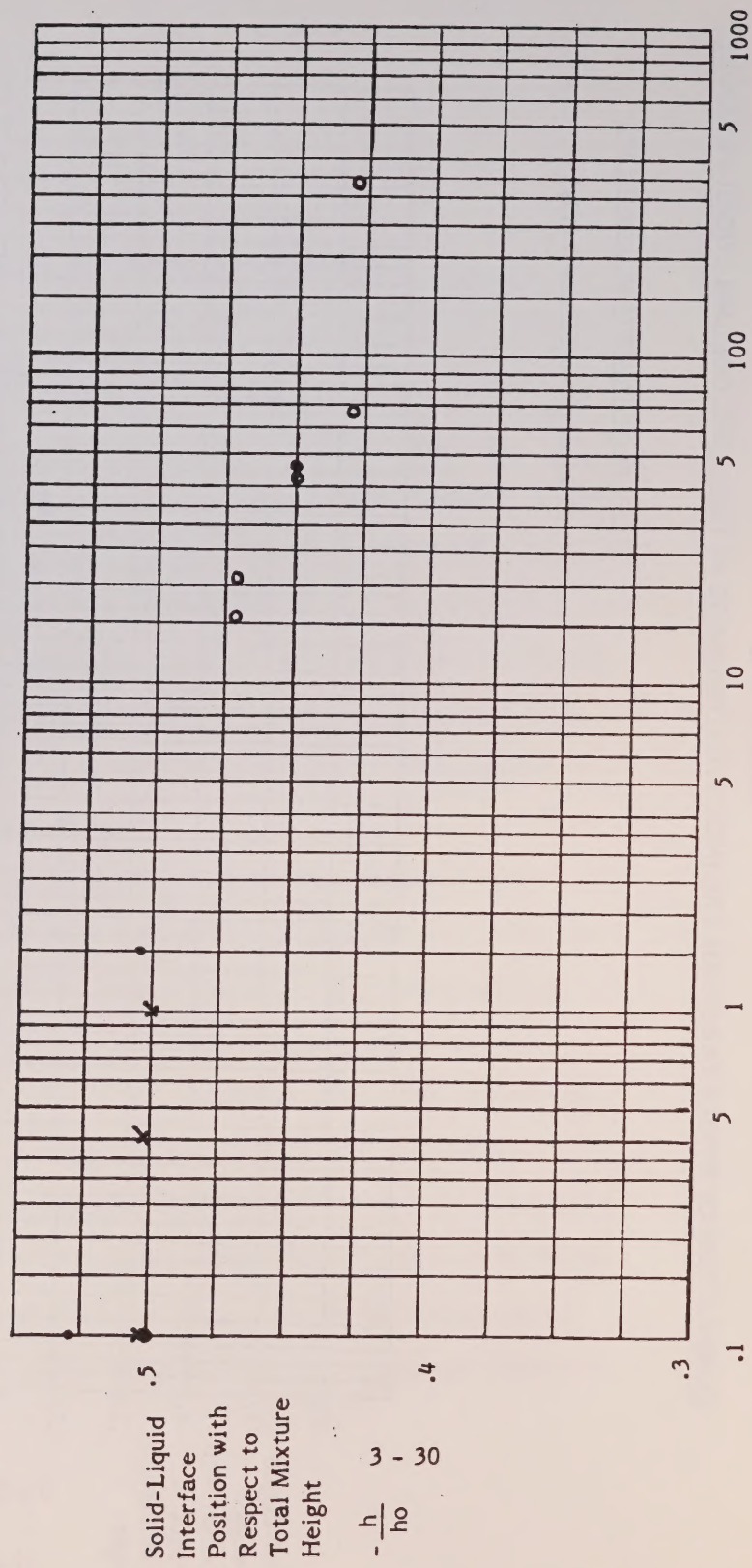
elapsed time - hours

FIGURE 3-13

COMPACTION OF THE SEDIMENT OF LIME COAGULATED (900mg/L CaO)
WHOLE TAR SANDS TAILINGS WITH DRAINAGE IN THE LONG COLUMN UNDER PRESSURE

Total pressure above sediment - psi

- 2 (layer of supernatant only)
- x 5
- o 15



elapsed time - hours

COMPACTION OF THE SEDIMENT OF LIME COAGULATED (900 mg/L CaO)
AND POLYELECTROLYTE FOLCCULATED (8mg/L Cyanimid A-110) WHOLE TAR
SANDS TAILINGS WITH DRAINAGE IN THE LONG COLUMN UNDER PRESSURE

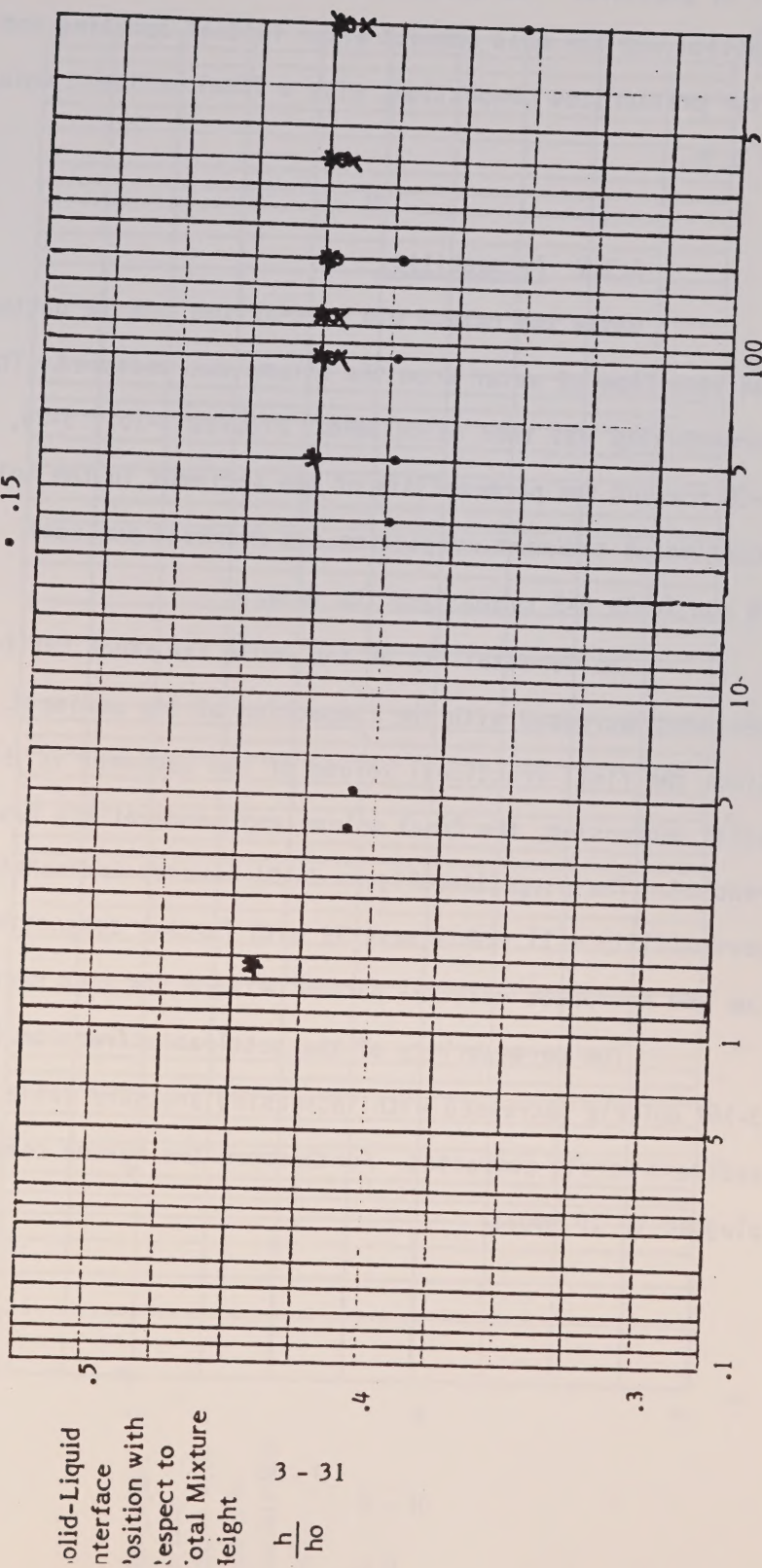
Total pressure above sediment - psi

* 2 (layer of supernatant only)

o 5

x 10

• .15



of lime and polyelectrolytes the sediment compacted 0.05 units under supernatant pressure and an additional 0.03 units under 15 psi of pressure. The sediment with lime and polyelectrolyte addition was the most compact after initial settling and also after pressurized compaction, with a final sediment volume (h/h_0) of 0.36.

3.3.2 Permeability

While the column was pressurized and the bottom drain was open flow of water from the column was measured. The permeability was then calculated. Figures 3-15, 3-16, 3-17 and 3-18 present the permeability of the sediment in the column as a function of sediment compaction and overhead pressure. Figure 3-19 and Table 3-5 summarizes the data.

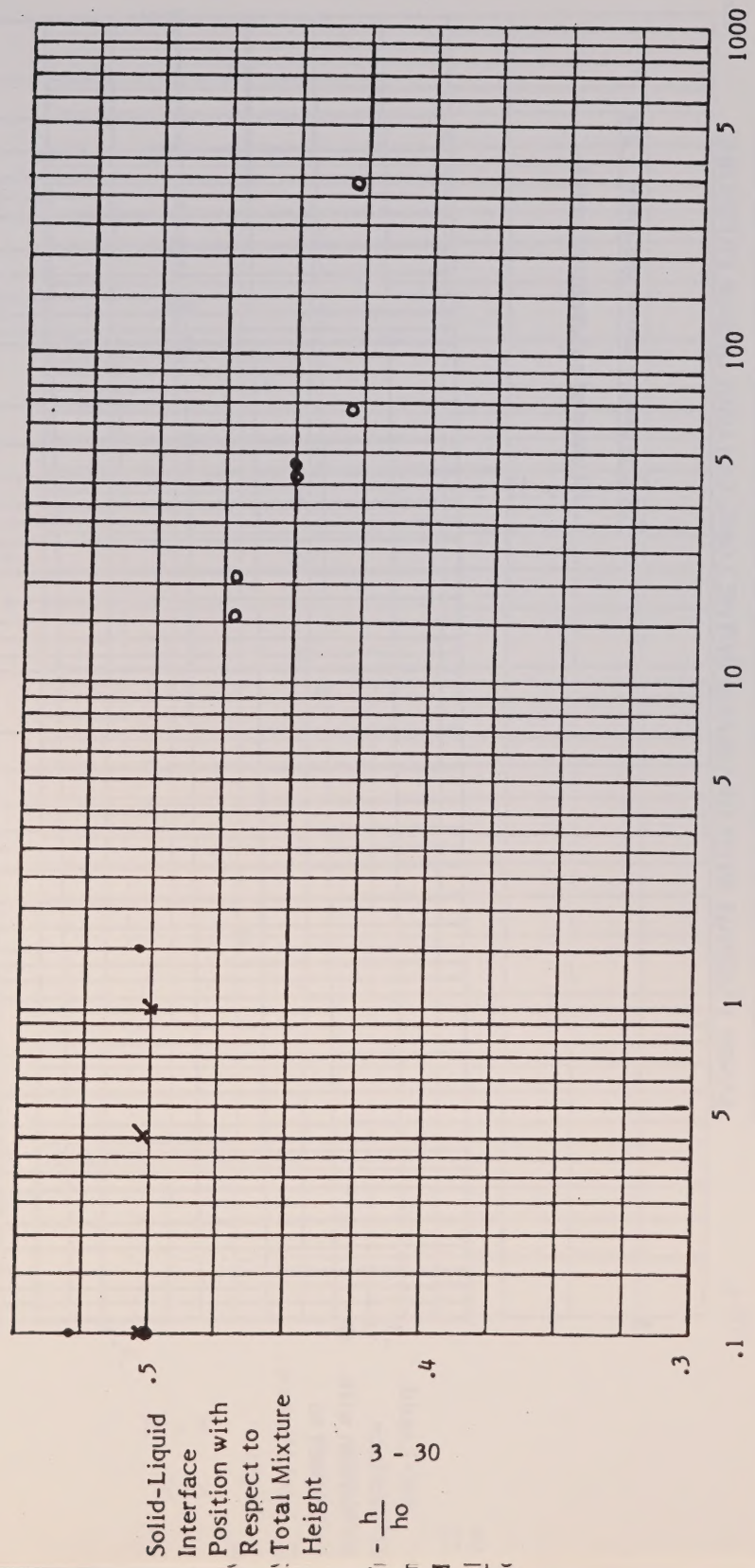
The permeability of the whole tar sands tailings sediment decreased with the compaction of the sediment. Since the final fractional volume of the sediment is .534 and still decreasing, the final volume and permeability has not been reached. The slope (see Figure 3-19) however indicates that the permeability will reduce severely with further compaction probably due the amorphous material packed between the sand particles.

The permeability of the settleable fraction (in Figure 3-16) quickly decreased with increasing pressure while the sediment barely compacted. Furthermore the column completely plugged in 19 hours.

COMPACTION OF THE SEDIMENT OF LIME COAGULATED (900mg/L CaO) WHOLE TAR SANDS TAILINGS WITH DRAINAGE IN THE LONG COLUMN UNDER PRESSURE

Total pressure above sediment - psi

- 2 (layer of supernatant only)
- x 5
- o 15



elapsed time - hours

FIGURE 3-14

COMPACTION OF THE SEDIMENT OF LIME COAGULATED (900 mg/L CaO)
AND POLYELECTROLYTE FOLCCULATED (8mg/L Cyanimid A-110) WHOLE TAR
SANDS TAILINGS WITH DRAINAGE IN THE LONG COLUMN UNDER PRESSURE

Total pressure above sediment - psi

* 2 (layer of supernatant only)

° 5

x 10

• .15

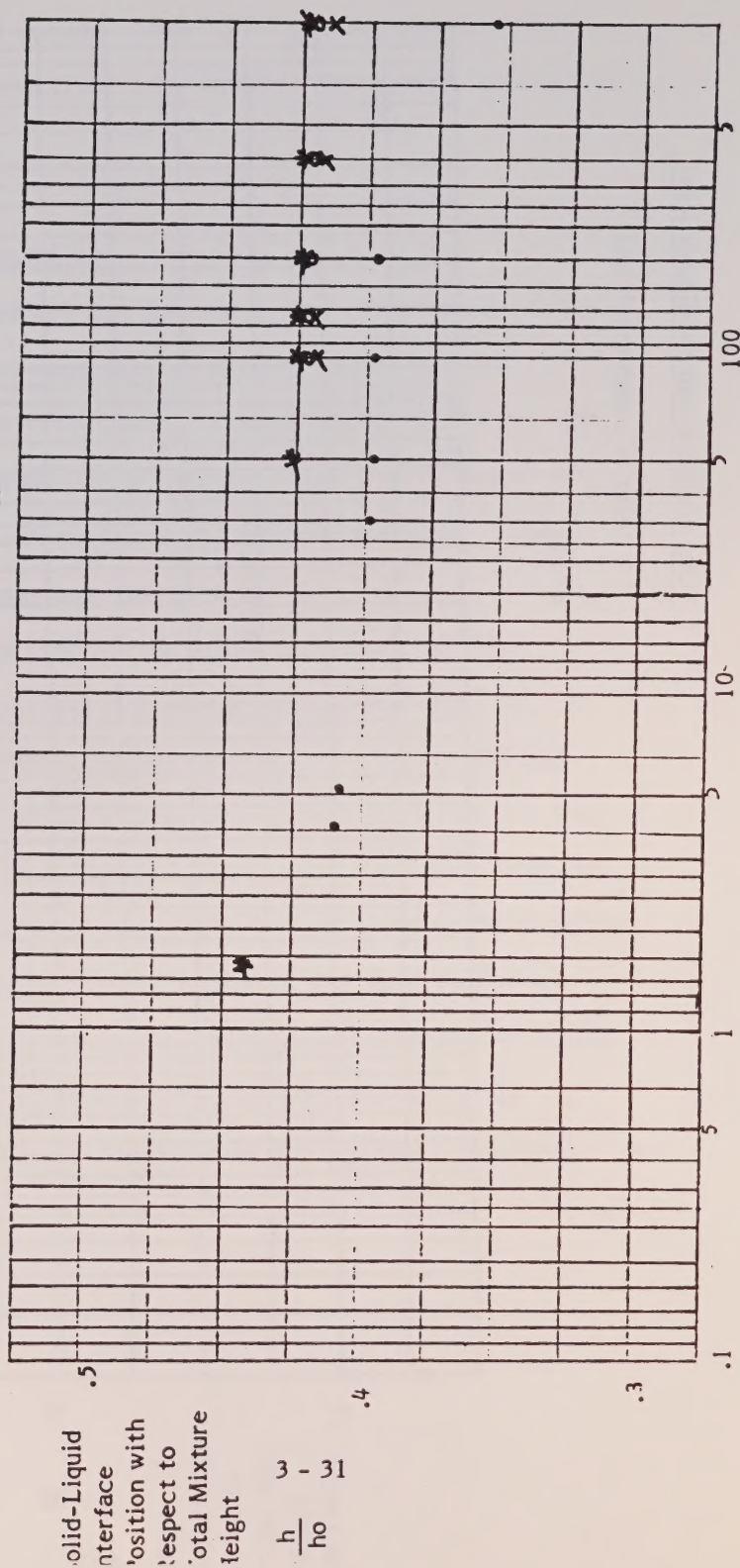
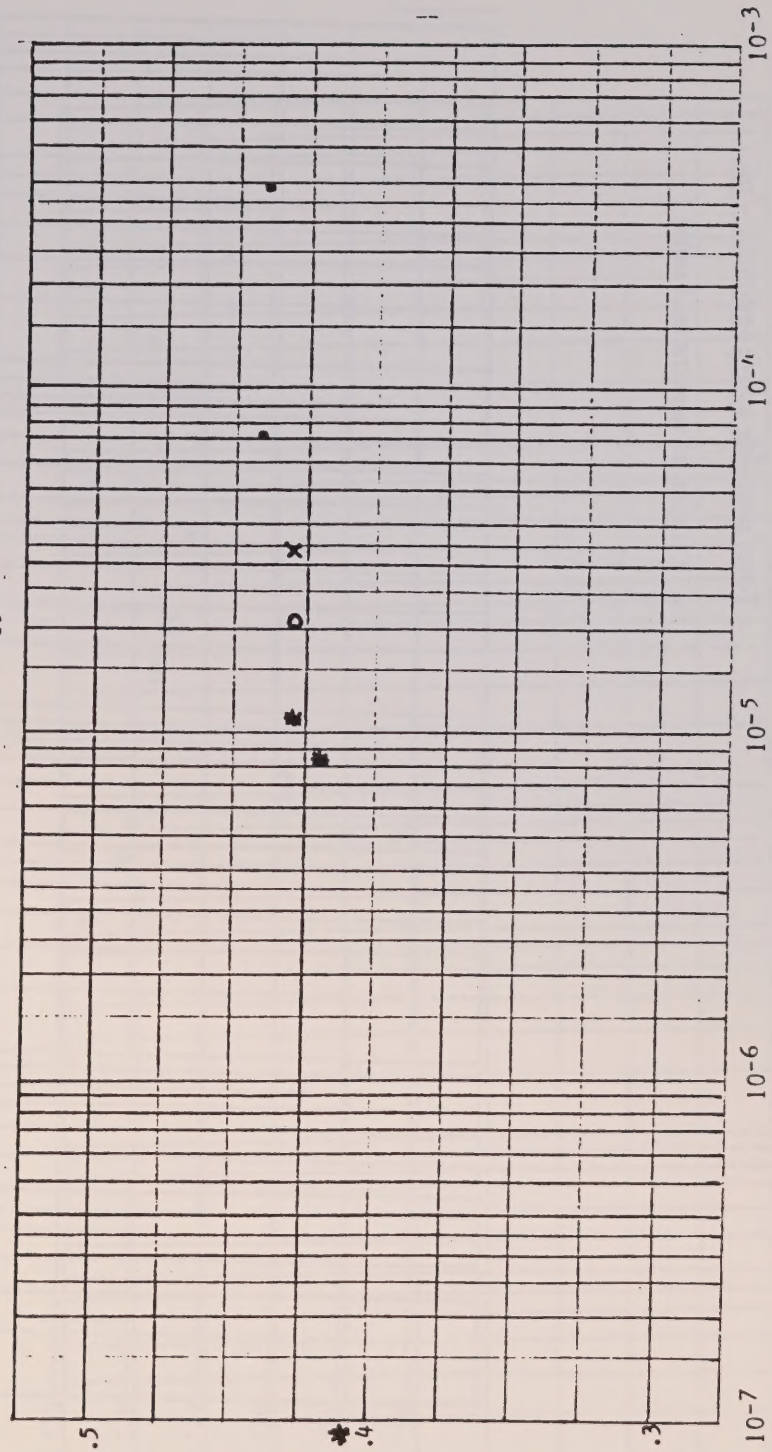


FIGURE 3-15

SEDIMENT PERMEABILITY AS FUNCTION OF COMPACTION
UNTREATED SETTLEABLE FRACTION OF WHOLE TAR SANDS TAILINGS

Total pressure above sediment - psi

- 2 (layers of supernatant only)
- x 5
- o 10
- * 15



3 - 33 Fractional Interface Height
 $\frac{-h}{h_0}$

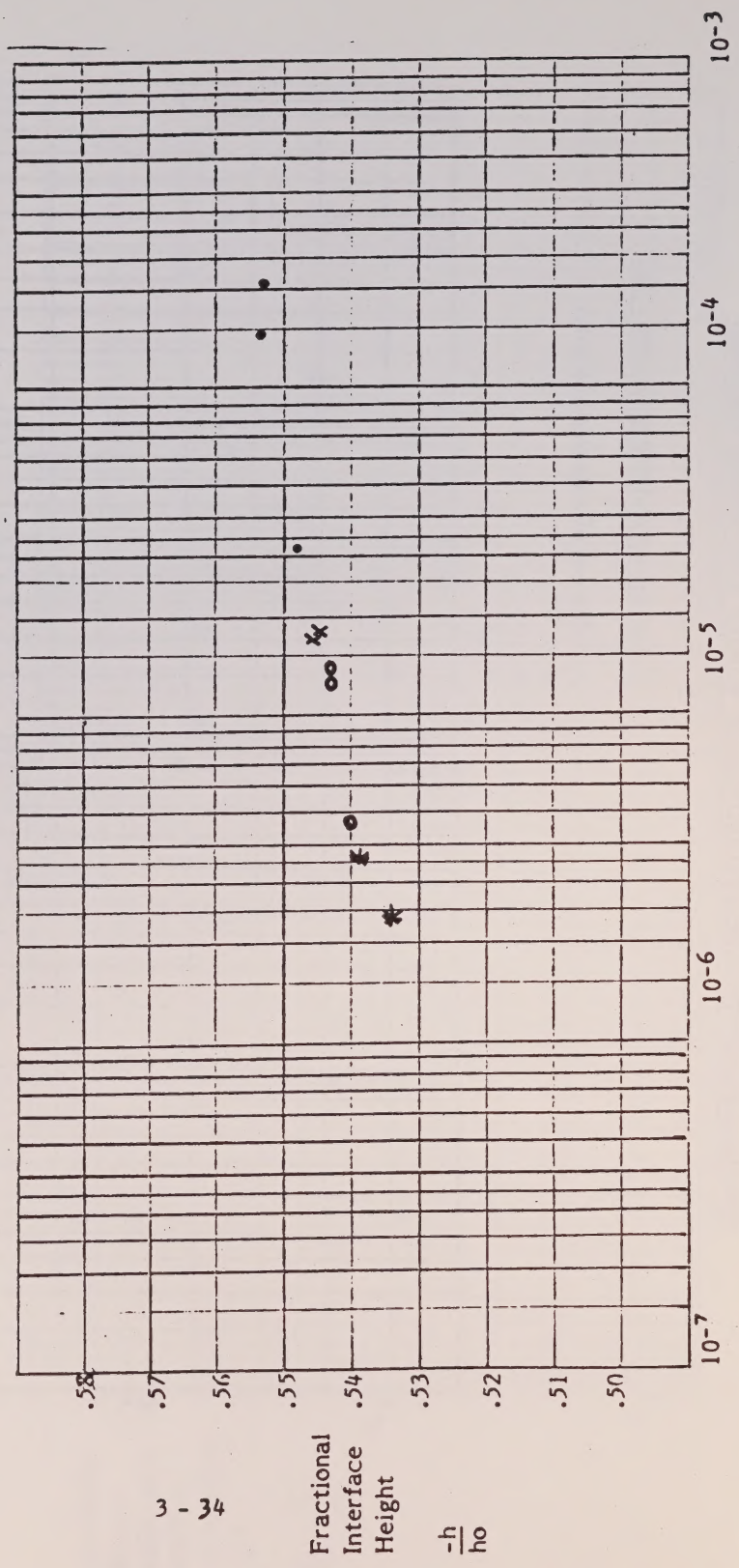
K - cm/sec

FIGURE 3-16

SEDIMENT PERMEABILITY AS FUNCTION OF COMPACTION IN WHOLE TAR SANDS TAILINGS

Total pressure above sediment - psi

• 2 (layer of supernatant only)
x 7
o 12
* 17



Permeability - cm/sec

FIGURE 3-17

SEDIMENT PERMEABILITY AS FUNCTION OF COMPACTION IN LIME
COAGULATED (900 mg/L CaO) WHOLE TAR SANDS TAILINGS

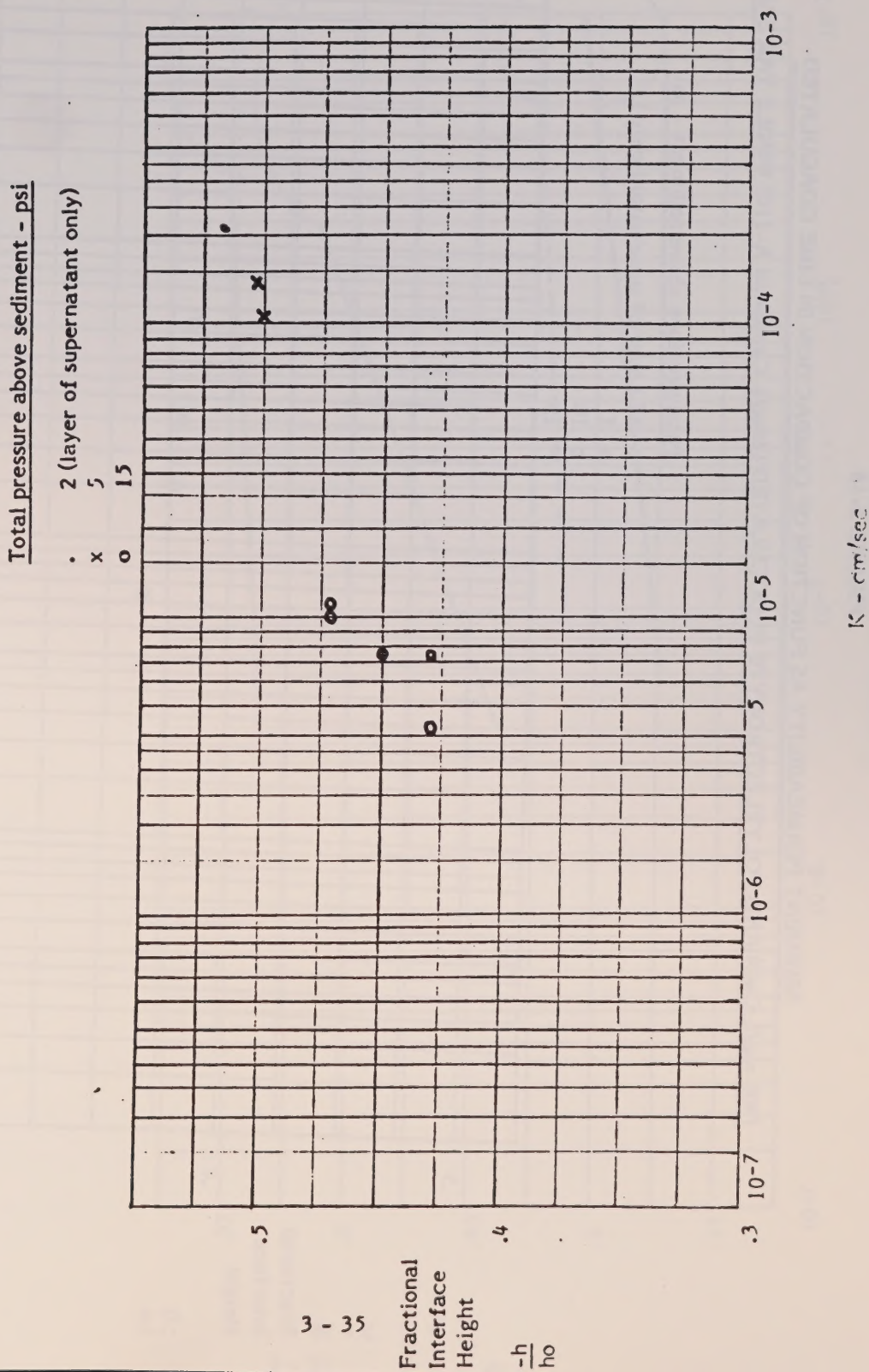


FIGURE 3-18

SEDIMENT PERMEABILITY AS FUNCTION OF COMPACTION IN LIME COAGULATED

(900 mg/L CaO) AND POLYELECTROLYTE FLOCCULATED (8mg/L Cyanamid A-110) WHOLE TAR SANDS TAILINGS

Total pressure above sediment - psi

• 2 (Layer of supernatant only)

x 5

o 10

* 15

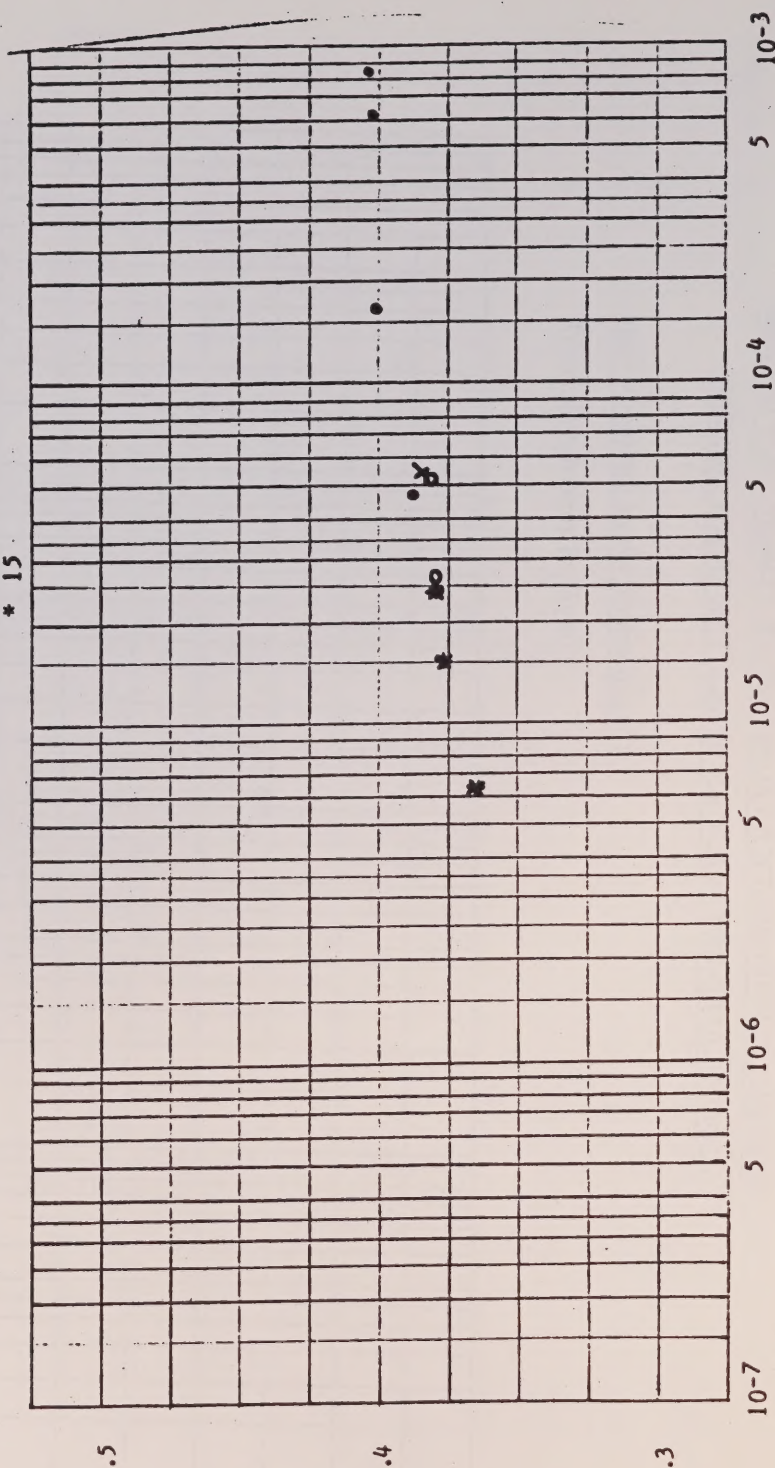
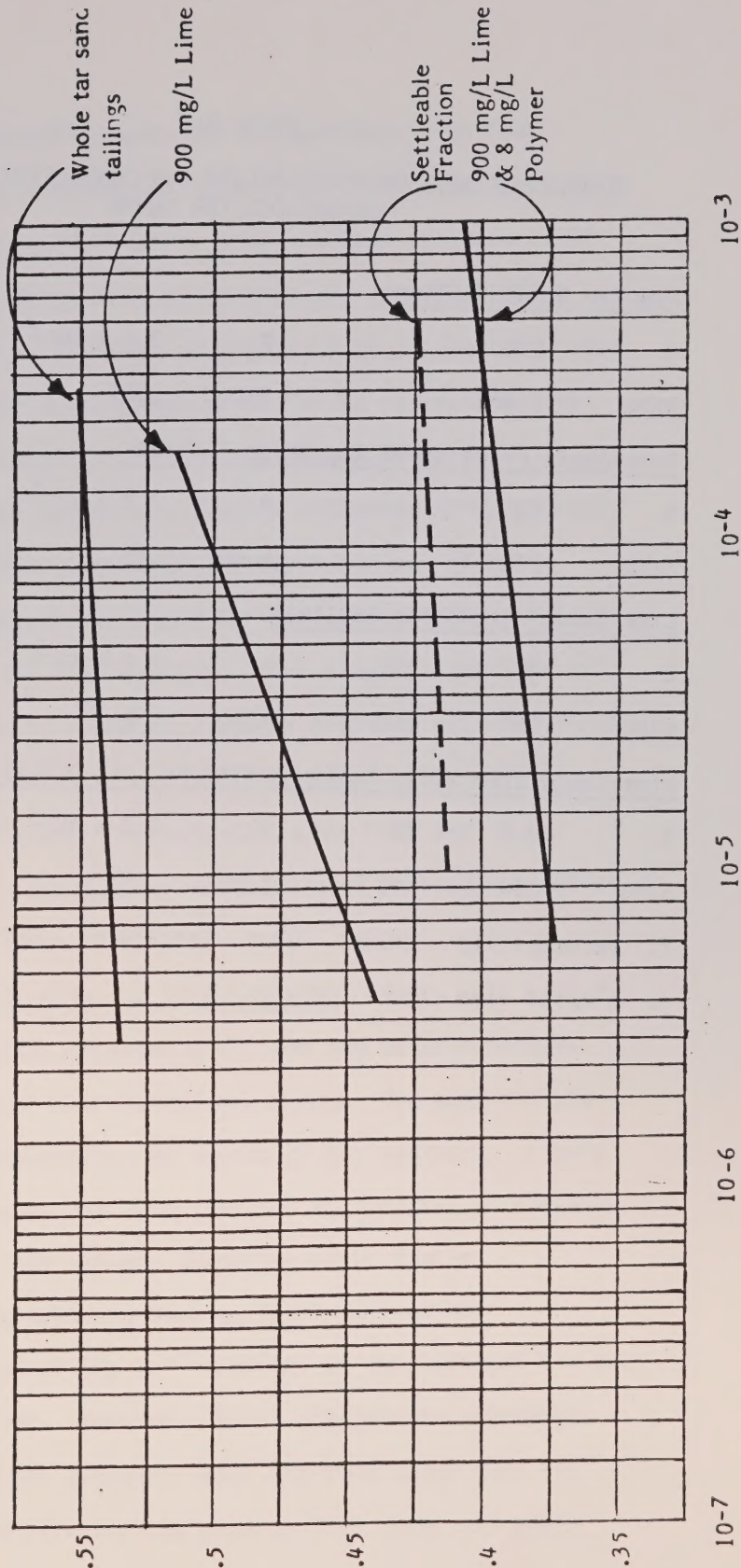


FIGURE 3-19

COMPARISON OF SEDIMENT PERMEABILITY AS FUNCTION OF COMPACTION END TREATMENT



Permeability - cm/sec Units

TABLE 3-5

SUMMARY OF DATA ON PERMEABILITY AND COMPACTION OF RAW AND
COAGULATED TAR SANDSRaw Tar Sands Tailings

t	240	P	3.2×10^{-5}	2.4×10^{-6}
h/ho	1.553	h/ho	.548	.534

Settleable Fraction of Tar Sands Tailings

t	48	P	7.2×10^{-5}	0
h/ho	.45	h/ho	.44	.41

Lime Coagulated Whole Tailings

t	35	260	P	2.2×10^{-4}	4.2×10^{-6}
h/ho	.57	.52	h/ho	.50	.43

Lime Coagulated Whole Tailings With Polymer Addition

t	3.5	25	P	4.7×10^{-5}	6.4×10^{-6}
h/ho	.44	.43	h/ho	.385	.366

P: permeability - cm/sec h/ho: fractional interface height

t: elapsed time - hours

The permeability data for the sediment with lime addition alone is presented in Figure 3-17. As stated earlier the sediment compacted 0.07 units with overhead pressure to 15 psi and the permeability reduced accordingly to 4.2×10^{-6} cm/sec. The slope of the line of points at 15 psi indicate that the sediment has not been compacted as far as it could be and that the final permeability has not been obtained.

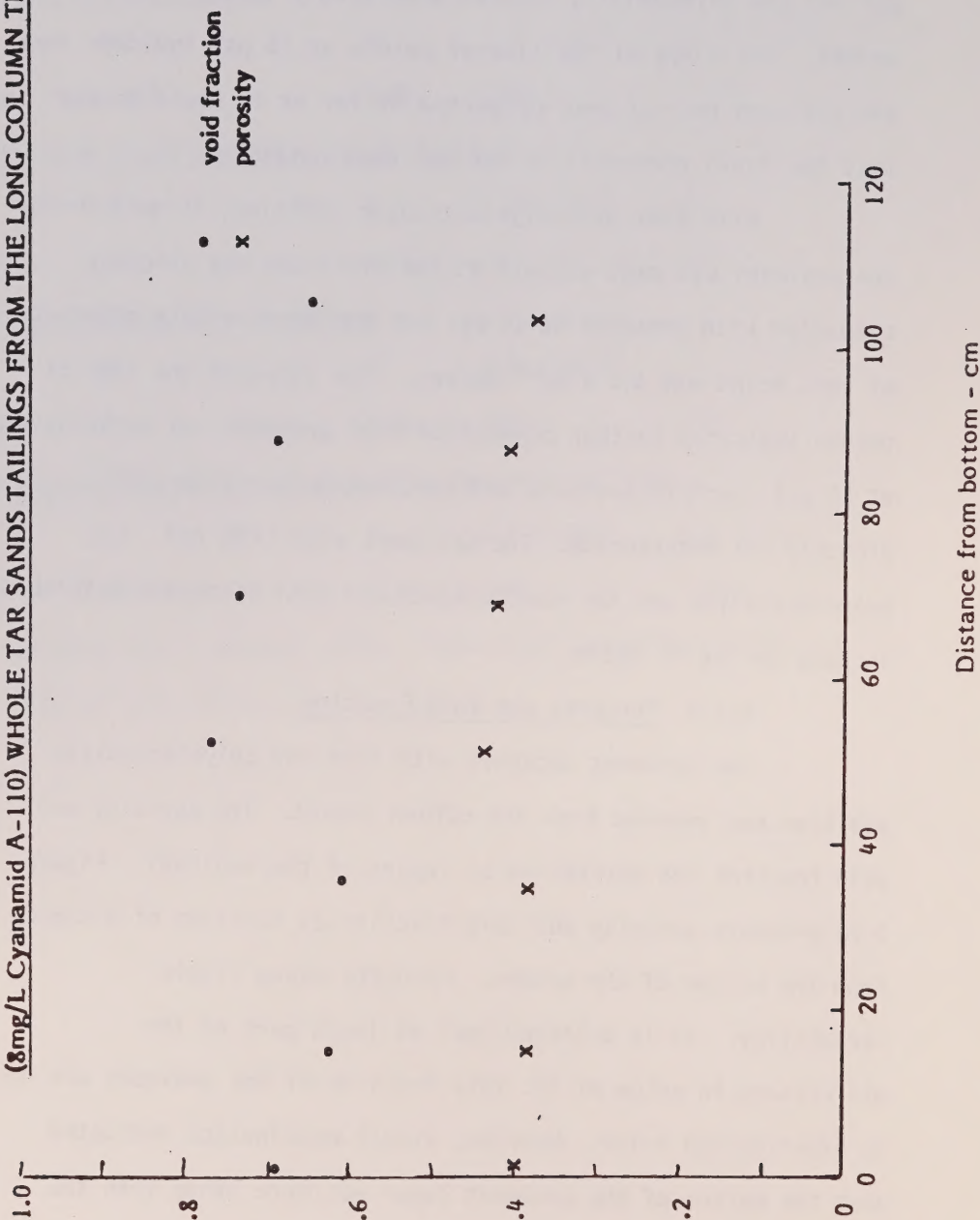
With lime and polyelectrolyte addition, (Figure 3-18), the sediment was most compact at the start and was slightly compacted with pressure to 15 psi and the permeability obtained at this point was 6.5×10^{-6} cm/sec. The slope of the line of points indicates further compaction will probably not be achieved at 15 psi overhead pressure and that the permeability will probably not deteriorate. The sediment with lime and polyelectrolyte was the most compact and most permeable obtained in this series of tests.

3.3.3 Porosity and Void Fraction

The sediment obtained with lime and polyelectrolyte addition was removed from the column intact. The porosity and void fraction was determined on layers of the sediment. Figure 3-20 presents porosity and void fraction as function of distance from the bottom of the column. Porosity shows little variability. It is believed that at least part of the differences in value of the void fraction of the sediment are due to experimental error. However, visual examination indicated that the bottom of the sediment layer was more sandy than the top. The use of polyelectrolyte ensures that large and small

FIGURE 3-20

POROSITY AND VOID FRACTION AT VARIOUS POSITIONS IN THE SEDIMENT OF
LIME COAGULATED (900 mg/L CaO) AND POLYELECTROLYTE FLOCCULATED
(8mg/L Cyanamid A-110) WHOLE TAR SANDS TAILINGS FROM THE LONG COLUMN TEST

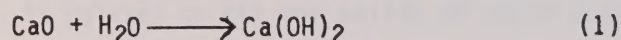


particles, such as sand and clay respectively, mesh as uniformly as possible, tending to form a homogeneous sediment. The averaged value of porosity was 0.4 and of void fraction was 0.67.

3.4 Fate of Lime

A knowledge of fate of lime added to tar sands tailings would provide useful information of the characteristics of the coagulated solids. Fate of lime was estimated from the chemical analysis and other available data.

The lime was slaked prior to dosing and the following reaction took place.



The slaked lime then reacts with the available alkalinity.

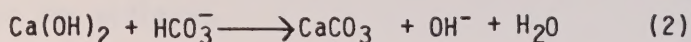
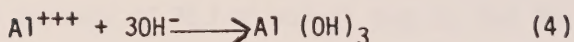
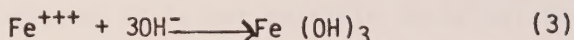


Table 3-6 lists the analysis of the raw and lime coagulated tar sands tailings supernatant. From Table 3-6 other cations that could have significant reactions are Fe and Al. Soluble salts of these metals would form hydroxides.



In Table 3-6 the magnitude of the iron and aluminum concentrations shown in the supernatants indicate that these species are present as colloidal solids and therefore not likely to form hydroxides to any appreciable extent. However, iron, aluminum and calcium are capable of complexing with clays and other chemical matrices with widely varying stoichiometry, which is difficult to quantitate.

TABLE 3-6

CHEMICAL COMPOSITION OF RAW AND LIME-TREATED
SUPERNATANTS OF TAR SANDS TAILINGS

CHEMICAL COMPOSITION OF THE SUPERNATANT OF RAW TAR SANDS TAILINGS

pH : 7.7
 Ca : 6 mg/L = 0.15 m moles/l
 Al : 140 mg/L = 5.19 m moles/l
 Fe : 12 mg/L = .24 m moles/l
 Na : 270 mg/L

Hardness: 32 mg/L as CaCO_3

Alkalinity (pH 3.7) 598 mg/L as CaCO_3 = 5.88 m moles/l as HCO_3

CHEMICAL COMPOSITION OF THE SUPERNATANT OF LIME COAGULATED TAR
SANDS TAILINGS

pH : 11.8
 Ca : 170 mg/L = 4.25 m mole/L
 Na : 390 mg/L
 Fe : <1 mg/L
 Fe : <.1 mg/L

Hardness: 236 mg/L as CaCO_3

Alkalinity:

(pH 8.3) : 1208 mg/L as CaCO_3

(pH 3.7) : 12.48 mg/L as CaCO_3

The 900 mg/L CaO dosage provides 16 m moles of Ca^{2+} , and 32 m moles of OH^- . An additional 0.15 m moles/L of Ca was present in the raw supernatant. Of the 16.15 m moles/L Ca 4.25 was precipitated as CaCO_3 and 6.02 m moles/L adsorbed on the solids or involved in complexes. The errors in analysis and the multiplication of errors in calculations could also account for the outstanding amount in the Ca balance. A total of 18.9 m moles/L Ca could adsorb on the solids in each litre of tar sand tailings (48% solids content by weight) according to the cation exchange capacity of 0.08 mg/L. The cation exchange capacity appears to be low when compared to pure clays (see Table 3-7). However, it relates to all the solids of which only 10% are clays. Overall 11.9 m moles/L, or 476 mg/L Ca was incorporated into the sediment.

Of the 32 m mole/L hydroxide supplied by the lime 6.3 m moles/L was used (by calculation) in raising the pH from 7.7 to 11.8. Iron and aluminum usually form hydroxide precipitates. However since the speciation of these elements in the raw sample is unknown it is not possible to calculate the amount reacted. The balance of 25.7 m mole/L may be due to involvement of OH^- in Ca complexes and errors in analysis and calculations.

The alkalinity after lime addition is mostly supplied by OH^- as carbonates have been precipitated. In complex wastes, such as tar sands tailings, however, the presence of other inorganic and organic chemicals contribute to alkalinity, and the resultant calculations are therefore an approximation only.

TABLE 3 - 7

CATION EXCHANGE CAPACITY OF VARIOUS TYPES OF CLAY

<u>Type of Clay</u>	<u>Cation Exchange Capacity</u>	
	mg/100g	mg/g
Kaolinite	3 - 15	.03 - .15
Halloysite	5 - 50	.05 - .5
Montmorillonite	80 - 150	.8 - 1.5
Illite	10 - 40	.1 - .4
Chlorite	10 - 40	.1 - .4
Vermiculite	100 - 150	1 - 1.5

3.5 Sediment Properties

3.5.1 Curing

A five gallon batch of whole tar sands tailings was coagulated with 900 mg/L CaO and flocculated with 8 mg/L Cyanamid A-110 polyelectrolyte. The sediment was mixed to a uniform consistency after the supernatant was decanted. Molds (5 cm id x 5 cm length) were filled with the sediment. Curing took place at room temperature and at 69°C in air, in humid air and saturated (under water). Similarly a set of high lime content samples were prepared with 3000 mg/L CaO added to the whole tar sands tailings

The compressive strength of each specimen was evaluated using the unconfined compressive strength (UCS) method.

Sediment specimen were cured for up to 190 days. At intervals during the curing period, specimens were removed for testing. The results of the UCS test is presented in Table 3-8. For the purposes of comparison Table 3-9 presents the UCS values of various types of soils.

Specimens cured under saturated conditions showed the least strength and by the end of the 190 day period the specimens had disintegrated. The specimens cured at room temperature were equivalent to extremely stiff soils (Table 3-9). Highest strengths were obtained with the specimens cured in contact with air. Whether the air was dry or humid, or the temperature was 20°C or 69°C the strength developed at corresponding times was of the same magnitude. The data scatter is such that detailed analysis cannot be justified. At the 28th day the specimen consistency was comparable to very strong soil to very weak rock

TABLE 3-8
UNCONFINED COMPRESSIBILITY STRENGTH AS
FUNCTION OF CURING TIME COAGULATED WHOLE TAR SANDS TAILINGS

UCS - Kg/cm ²										
Elapsed Time/Days	COAGULATED WITH 900 mg/L CaO AND 8 mg/L A-110				COAGULATED WITH 3000 mg/L CaO					
	Room Temperature				69oC					
	air dry	humid air	saturated	air dry	humid air	saturated	air dry	humid air	saturated	
0	7.05									
7	8.87	11.92	2.59	9.63	9.06	1.39				
14	10.86	8.87	5.82	9.70	10.07	4.20	5.64	5.13	3.81	
28	11.27	12.47	5.59	11.64	10.07	3.23	-	5.08	-	
190	6.82	5.08	-*	7.77	6.10	-*	-	2.39	-	

* Specimen disintegrated.

TABLE 3-9

UNCONFINED COMPRESSIBILITY STRENGTHS OF VARIOUS SOILS AND ROCKS

	Kg/cm ²
Soft Soil	.25 - .5
Medium Soil	.5 - 1
Stiff Soil	1 - 2
Very Stiff Soil	2 - 4
Extremely Stiff Soil	4 - 6
Strong Soil	6 - 8
Very Strong Soil or Extremely Weak Rock	8 - 10
Very Weak Rock	<12.5

(see Table 3-9). By the 190th day strength of all specimens had deteriorated to that of extremely stiff soil.

Specimens made up with 3000 mg/L CaO showed substantially lower strength than specimens made up with 900 mg/L. Thus excessive lime addition was detrimental rather than beneficial.

3.5.2. Pozzolanic Reactivity

The pozzolanic reactivity of raw and lime treated whole tar sands tailings sediment specimen was evaluated with UCS testing, thermal analysis and XRD analysis. The results of the UCS testing are presented in Table 3-10. The very weak strength of the specimens indicates that pozzolanic reactions did not take place. The detailed results of thermal analysis, carried out at the Wastewater Technology Centre of EPS at Burlington Ontario, are shown in the Appendix. These results also indicate that pozzolanic reactions did not take place.

The XRD analysis (detailed report in the Appendix) found that the major component of the sediment of the raw tar sand tailings was quartz. The minor components were feldspar, illite and kaolin. The sediment from coagulated whole tar sands tailings (900 mg/L CaO) was identical to the sediment of the raw tar sands tailings. The sediment sample containing 10% CaO consisted of $\text{Ca}(\text{OH})_2$ and CaCO_3 in addition to the minerals found in the raw sediment sample.

The UCS, thermal and XRD analysis collaborate that pozzolanic reaction did not take place in any of the specimens.

TABLE 3-10
POZZOLANIC REACTIVITY

<u>Specimen</u>	<u>7 days</u>	<u>158 days</u>
Evaporated Whole Tar Sands Tailings	0.18	
3000 mg/L CaO Added to Whole Tar Sands Tailings	0.18	.94
Evaporated Tar Sands Tailings with 10% CaO	0.37	.84
Evaporated Tar Sands Tailing with 20% CaO	0.37	2.39
900 mg/L CaO added to Whole Tar Sands Tailings		1.74

It is believed that the presence of large amounts of sand precludes pozzolanic reactions as sand will not react and separates the components that would react. Furthermore, the bitumen in the sample may poison the reactive materials, inhibiting any reaction.

3.6 Supernatant Treatability

Since a large quantity of water is used in the tar sands extraction and the tailings are separated from the water at some expense, as much of the water as possible should be reused. While part of the water can potentially be recycled to the extraction process, part may require disposal to prevent the build-up of dissolved inorganic constituents. Study objectives required the development of treatment methods to permit the use of water for oil field steam generation and for discharge to surface water.

The water quality requirements for recycle to process are less than 0.1% suspended solids and pH in the low alkaline range. Boiler feed water should contain less than 1 mg/L hardness, less than 150 mg/L silica and should be oil-free.

Syncrude's present operating permit does not allow discharge to surface waters. As a starting point, the discharge regulations for Alberta oil refineries were interpreted to provide target concentrations for surface discharge. The targets set included a COD of 200 mg/L COD or the TOC equivalent (COD is usually 2-3 times TOC in raw samples), 10 mg/L oil and grease, 25 mg/L suspended solids, 1 mg/L phenol, and 12.5 mg/L ammonia

nitrogen. Target pH was set in the range of 6.0 to 9.5. The maximum target concentrations of heavy metals in effluents are listed in Table 3-11.

The tests carried out in this phase of the study were aimed at devising a treatment scheme capable of achieving and where possible surpassing the above criteria at reasonable cost. Based on previously published results (McKinnon 1981) ammonia and phenol levels should present no problem, (range of ammonia concentration 4.9-8.2 mg/L, range of phenol 0.21 - 0.65 mg/L). The analyses in this study showed ammonia of 6 mg/L and phenol at 0.03 mg/L.

The tests carried out included coagulation with lime and dolomitic lime, post coagulation with alum, recarbonation, activated carbon adsorption and water softening. The rationale for these treatments is given below.

Dolomitic lime is a potential alternative coagulant to conventional lime. Post coagulation with alum is a possible means of controlling silica levels, should this be required for recirculation of water to the extraction process.

Recarbonation is a potential means of precipitating excess calcium and restoring pH to the low alkaline range for return to process. CO_2 is preferred to mineral acid for pH adjustment because it should be readily available locally at low cost and can be used to accomplish pH adjustment without adding conservative anions, such as chloride or sulphate.

Activated carbon adsorption is a potential means of reducing residual organics in the water to permit surface

TABLE 3-11

TARGET EFFLUENT CONCENTRATION FOR TOXIC HEAVY METALS

METAL	MAXIMUM ALLOWABLE DISCHARGE CONCENTRATION - mg/L
Chromium (hexavalent)	0.3
Lead	0.10
Mercury	0.0005
Zinc	1.0
Nickel	1.0

discharge. Ion exchange softening is a means of removing residual calcium from the lime-coagulated water, as part of a treatment scheme for boiler feed water preparation. Control of silica is important in process water, since amorphous colloidal silica can form glass-like deposits on heat exchange surfaces. In boilers, levels of silica above 150 mg/L can form scaling precipitates containing cations such as Ca^{++} , Mg^{++} and Fe^{++} . Lime coagulation and recarbonation is a potential means of controlling heavy metal levels in both the return process water and discharge streams.

3.6.1 Coagulation

The phase of the work concentrated on the removal of hardness, silica and toxic metals including mercury, during coagulation.

The coagulation was carried out in the jar tester described earlier. The first series of tests compared the constituents of an unfiltered and filtered (through 0.2 μ membrane) supernatant resulting from whole tar sands tailings coagulated with 900 mg/L CaO .

In the second series of tests the whole tar sands tailings was dosed with CaO between 500 and 2000 mg/L and the resulting supernatant was recarbonated to pH 7.5. In the third series of tests the whole tar sands tailings was dosed with dolimitic lime (CaO/MgO) at levels equivalent with the CaO dosages used in the second set of tests and the supernatant was recarbonated. In the fourth series of tests the whole tar sands

tailings was dosed with 900 mg/L CaO and the resulting supernatant was coagulated with 800-1500 mg/L alum.

The results of these tests are presented in Table 3-12. All the samples listed were filtered through a glass fiber filter prior to analysis, thus only the soluble chemical species were quantitated.

The results of the first series of tests showed that there were no appreciable differences between the filtered and unfiltered supernatant. The resultant suspended solids level was also below 10 mg/L. This indicates that the chemical species of interest were in solution.

Results of the second series of tests show that increasing the lime dosage above 1000 mg/L CaO will progressively reduce silica levels. With this sample of whole tar sands tailings the supernatant contained a maximum of about 20 mg/L silica (Table 3-13) versus reported values in excess of 100 mg/L in previous tests (Table 3-2). Because silica alone has a very high solubility at pH's above 10 (Figure 3-21) it is possible that high silica levels may be encountered in a full-scale facility. However, silica can be precipitated by a variety of cations at high pH. In this study attempts to artificially increase dissolved silica levels, by spiking with sodium silicate resulted in the progressive precipitation of calcium until all calcium was removed from solution. This is consistent with the low calcium concentrations at high silica concentrations shown in Table 3-12.

TABLE 3-12 RESULTS OF COAGULATION TESTS

	CaO DOSE mg/l	CaO/MgO DOSE mg/l	ALUM DOSE mg/l	CO ₂ ADDED FOR CARBONATION TO pH 7.5	Ca mg/l	Na mg/l	Si mg/l as SiO ₂	Hg μg/l	pH	HARDNESS mg/l as CaCO ₃	ALKALINITY phenolph methyl org mg/l as CaCO ₃
1st SET	900	-	-	-	99	340	6.5	0.08	11.6	236	1012
	900	**	-	-	96	320	6.5	0.21	11.6	270	1024
2nd SET	500	-	-	-	6	240	9.8	0.29	10.6	(15)*	368
	700	-	-	-	95	320	5.5	0.13	11.4	(237)*	896
	900	-	-	-	170	330	3.7	0.07	11.8	236 (425)*	1208
	1100	-	-	-	290	340	1.7	0.03	11.6	(725)*	1730
	1500	-	-	-	540	330	0.5	0.08	11.8	(1350)*	2553
	2000	-	-	-	670	340	<0.2	0.14	12.3	868 (1675)*	3189
	500	-	-	yes	10	310	(23.4)	(5.49)	7.2	(25)*	562
	700	-	-	yes	37	310	5.6	0.10	7.1	(92.5)*	694
	900	-	-	yes	29	330	3.7	0.10	7.4	(72.5)*	654
	1100	-	-	yes	42	330	8.5	0.08	7.8	(105)*	724
	1500	-	-	yes	42	320	0.6	0.03	7.1	(105)*	738
	2000	-	-	yes	28	340	<0.2	0.03	7.0	(70)*	712
3rd SET	-	430	-	-	18	280	2.6	0.15	9.4	24	197
	-	601	-	-	5	280	3.7	0.38	10.0	12	186
	-	773	-	-	6	270	8.5	0.30	10.4	12	232
	-	955	-	-	6	280	10.0	0.35	10.4	8	224
	-	1288	-	-	8	300	9.0	0.05	11.3	70	520
	-	1719	-	-	62	320	3.8	0.08	11.7	152	868
	-	430	-	yes	6	280	3.0	0.56	7.9	32	492
	-	601	-	yes	5	270	3.7	0.43	7.6	16	462
	-	773	-	yes	7	260	8.5	0.26	7.5	24	438
	-	955	-	yes	8	280	10.1	0.15	7.7	7(20)*	412
	-	1288	-	yes	10	310	9.2	0.03	7.8	4(25)*	588
	-	1719	-	yes	67	330	3.7	0.03	7.8	152	568
4th SET	900	-	800	-	69	330	3.3	0.03	11.2	172	368
	900	-	1000	-	76	330	<0.2	0.06	9.9	184	244
	900	-	1200	-	66	340	<0.2	0.08	9.7	184	96
	900	-	1300	-	73	330	<0.2	0.04	9.2	156	88
	900	-	1400	-	79	340	<0.2	0.03	9.2	164	70
	900	-	1500	-	86	330	<0.2	0.08	8.4	188	40

() * HARDNESS CONTRIBUTED BY Ca⁺⁺, as calculated from Ca⁺⁺ ion concentration.

** FILTERED THROUGH 0.2μ MEMBRANE

TABLE 3-13

RESULTS OF ICP AND IC ANALYSIS

ICP ANALYSIS

Sample ID	AG PPM	AL PPM	B PPM	BA PPM	BE PPM	CA PPM	CD PPM	CO PPM	CR PPM
T1	<.005	.03	1.33	.030	<.0005	6.56	<.01	<.05	<.01
T2	<.005	1.48	3.33	.017	<.0005	82.2	<.01	.05	<.01

Sample ID	CU PPM	FE PPM	K PPM	MG PPM	MN PPM	MO PPM	NA PPM	NI PPM	P PPM
T1	.021	<.01	6	3.37	.07	<.3	271	<.05	<.6
T2	.015	.02	13	<.01	<.01	<.3	397	<.05	<.6

Sample ID	PB MG/L	SI PPM	SR PPM	TH PPM	TI PPM	V PPM	ZN PPM	ZR PPM
T1	<.1	2.11	.164	<.01	<.005	<.005	<.05	<.05
T2	<.1	5.90	.545	.02	<.005	.036	<.05	.05

IC ANALYSIS

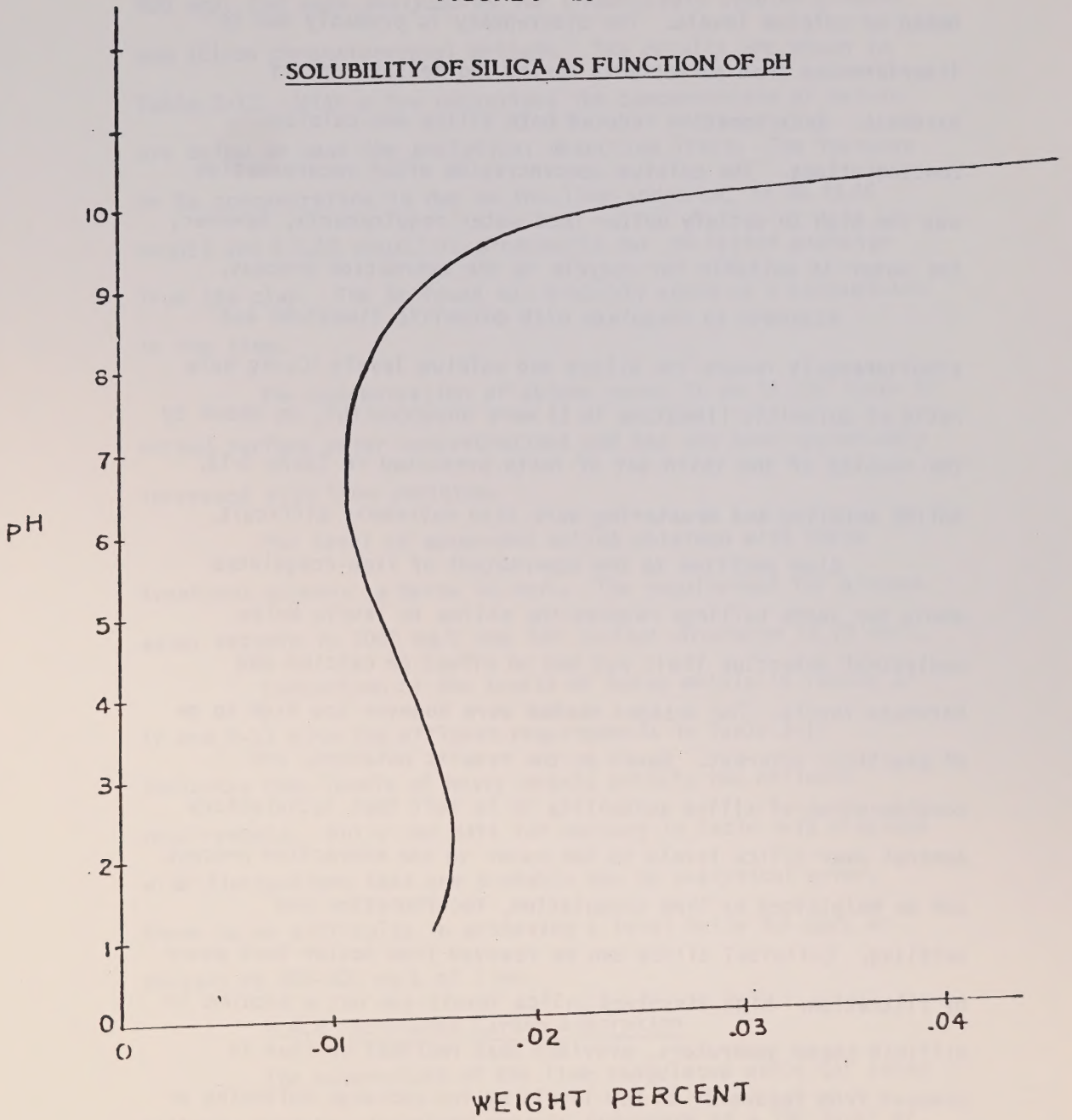
Sample ID	F ⁻ MG/L	Cl ⁻ MG/L	PO ₄ ⁻³ MG/L	NO ₃ ⁻ MG/L	SO ₄ ⁻² MG/L
T1	3.55	72.3	<.1	.32	127
T2	5.45	82.4	<.1	.49	158

T1 - Filtered supernatant of whole tar sands tailings.

T2 - Filtered supernatant of 900 mg/L CaO coagulated whole tar sands tailings.

FIGURE 3 - 21

SOLUBILITY OF SILICA AS FUNCTION OF pH



Silica removal upon lime addition was accompanied by an up to 10 fold increase in calcium and hardness concentration. The measured hardness was lower than the calculated hardness based on calcium levels. The discrepancy is probably due to interferences from surfactants during the measurement of hardness. Recarbonation reduced both silica and calcium concentrations. The calcium concentration after recarbonation was too high to satisfy boiler feed water requirements, however, the water is suitable for recycle to the extraction process.

Attempts to coagulate with dolomitic limestone and simultaneously reduce the silica and calcium levels (Ca:Mg mole ratio of dolomitic limestone is 1) were unsuccessful, as shown by the results of the third set of tests presented in Table 3-12. Solids settling and dewatering were also extremely difficult.

Alum addition to the supernatant of lime-coagulated whole tar sands tailings reduced the silica to levels below analytical detection limit but had no effect on calcium and hardness levels. The dosages needed were however too high to be of practical interest. Based on the results obtained, and consideration of silica solubility it is felt that satisfactory control over silica levels in the water to the extraction process can be maintained by lime coagulation, recarbonation and settling. Colloidal silica can be removed from boiler feed water by filtration. High dissolved silica levels are not a problem in oilfield steam generators, provided that residual calcium is removed from feedwater to low levels by ion exchange softening or other means.

Samples of filtered raw whole tar sands tailings and of filtered supernatant of whole tar sands tailings coagulated with 900 mg/L CaO were analyzed by ICP (inductively coupled plasma) and IC(ion chromatography) methods. The results are shown in Table 3-13. With a few exceptions the concentration of metals are below or near the analytical detection limit. The increase in Ca concentration is due to the lime addition, in Na (5.48 mg/L) and K (.18 mg/L) is presumably due to cation exchange from the clay. The Sr found was probably added as a contaminant in the lime.

The concentration of anions seems to be in the range of normal surface water concentrations and has not been appreciably increased with lime addition.

The level of suspended solids obtained with these treatment schemes is below 10 mg/L. The requirement for process water recycle is 1000 mg/L and for surface discharge is 25 mg/L.

Comparison of the levels of heavy metals in Tables 3-12 and 3-13 with the effluent requirements in Table 3-11 indicates that levels of heavy metals satisfy the effluent requirements. While the data for mercury in Table 3-12 displays wide fluctuations that are probably due to analytical error, there is no difficulty in achieving a level below 0.5 ug/L at dosages of 800-900 mg/L of lime.

3.6.2 Activated Carbon Adsorption

The supernatant of the lime coagulated whole tar sands tailings contains dissolved organic compounds at a TOC level of 90 mg/L and hexane extractables at 46 mg/L. There was no

suspended oil. While this organics level is acceptable for in-plant use, and as steam generator feed-water, its possible discharge to surface waters is questionable. Adsorption on activated carbon is a potentially viable method of reducing the organic concentration further.

GC/MS analysis of the supernatant indicates that the organics present are hydrocarbons, and hydrocarbons containing oxygen. Figure 3-22 presents the total ion chromatogram showing a large number of closely related compounds indicated by the large envelope. The mass spectrum of the apex of the peak in Figure 3-22 is shown in Figure 3-23. The series of lines are characteristics of hydrocarbons. The possible identity of the compound at the peak is shown in Figure 3-24. In summary, these compounds composed 97% of the dissolved organics.

The adsorption isotherms obtained for the supernatant of whole tar sands tailings coagulated with 900 mg/L CaO with Filtrasorb 400 activated carbon are shown in Figure 3-25. Isotherms based on both TOC and hexane extractables are presented. Both isotherms are typical of difficult to adsorb compounds. While the hexane extractables reduced to zero the total organic carbon (TOC) did not. The equilibrium loading of the carbon appears to be 150 mg TOC/g carbon. The TOC of the water includes nonadsorbable, and non extractable compounds as shown by the differences between the two isotherms. This indicates the presence of polar organics. The shape of the TOC based isotherm is similar to isotherm obtained with organic acids (Mattson and Marks, 1971). A likely compound is naphthenic acid

MASS CHROMATOGRAM OF EXTRACT OF UNDERIVATIZED TAR SANDS COAGULATED SUPERNATANT

MASS CHROMATOGRAMS

DATA: TSA #583

SCANS 400 TO 1200

04/12/84 10:47:00

CALI: CALI1104 #3

SAMPLE: 1UL TSA STD UNDERIVATIZED @ 2.5 UG/UL

CONDS.: DB5/PP/0EM

RANGE: G 1,1200 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3

586

562

454

100.0

95

13.7

99

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± 0.500

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± 0.50

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109.

MASS SPECTRUM OF EXTRACT OF UNDERIVATIZED TAR COAGULATION SUPERNATANT

RIC

04/12/84 10:47:00

DATA: TSA #583

SCANS 400 TO 1200

CALI: CALI1104 #3

SAMPLE: IUL TSA STD UNDERIVATIZED @ 2.5 UG/UL

COND.: DB5/PP/QEM

RANGE: G 1.1200

LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3

613

100.0

688

RIC

42048.

MASS SPECTRUM OF THE PEAK AT 15 MINUTES RETENTION TIME IN FIGURE 3-22 WITH POSSIBLE MATCHES FROM THE LIBRARY

LIBRARY SEARCH
04/12/84 10:47:00 + 9:45
SAMPLE: 1UL TSA STD UNDERIVATIZED @ 2.5 UG/UL
COND5.: DB5/PP/OEM

DATA: TSA # 586
CALI: CALI1104 # 3
BASE M/Z: 95
RIC: 16175.

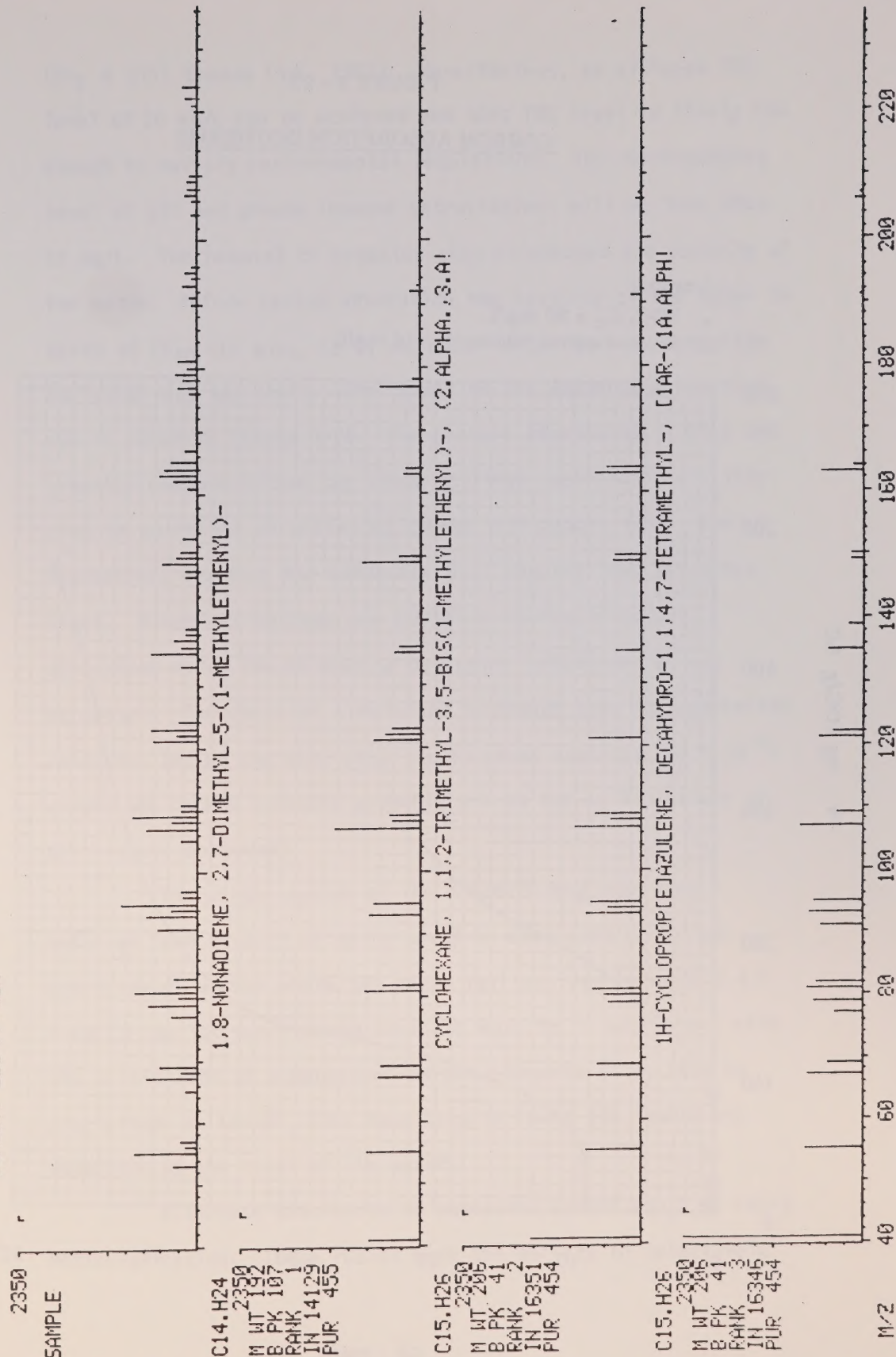


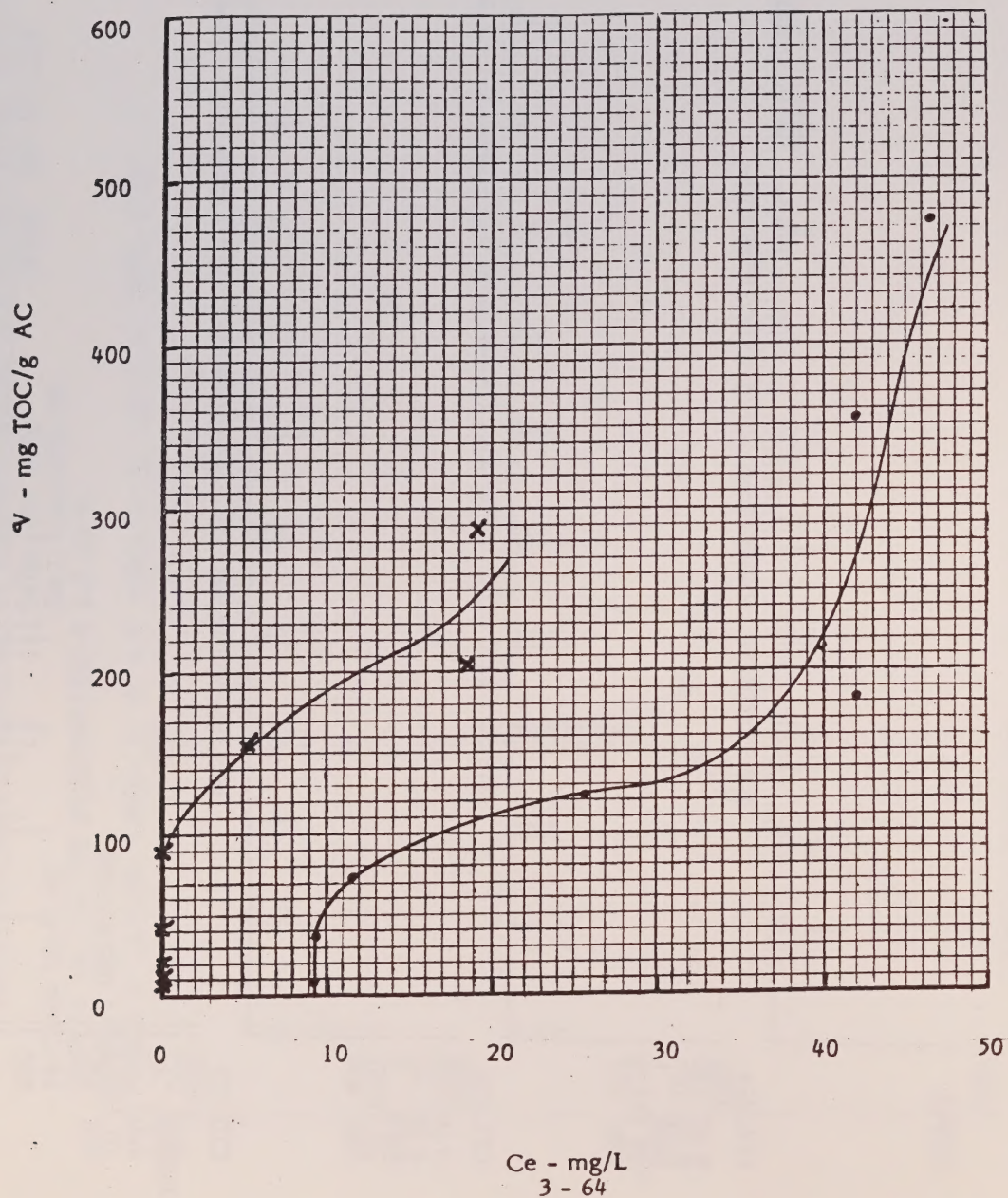
FIGURE 3 - 25

CARBON ADSORPTION ISOTHERMS

Legend:

• TOC, $C_0 = 90$ mg/L

x Hexane extractables: $L_0 = 46$ mg/L



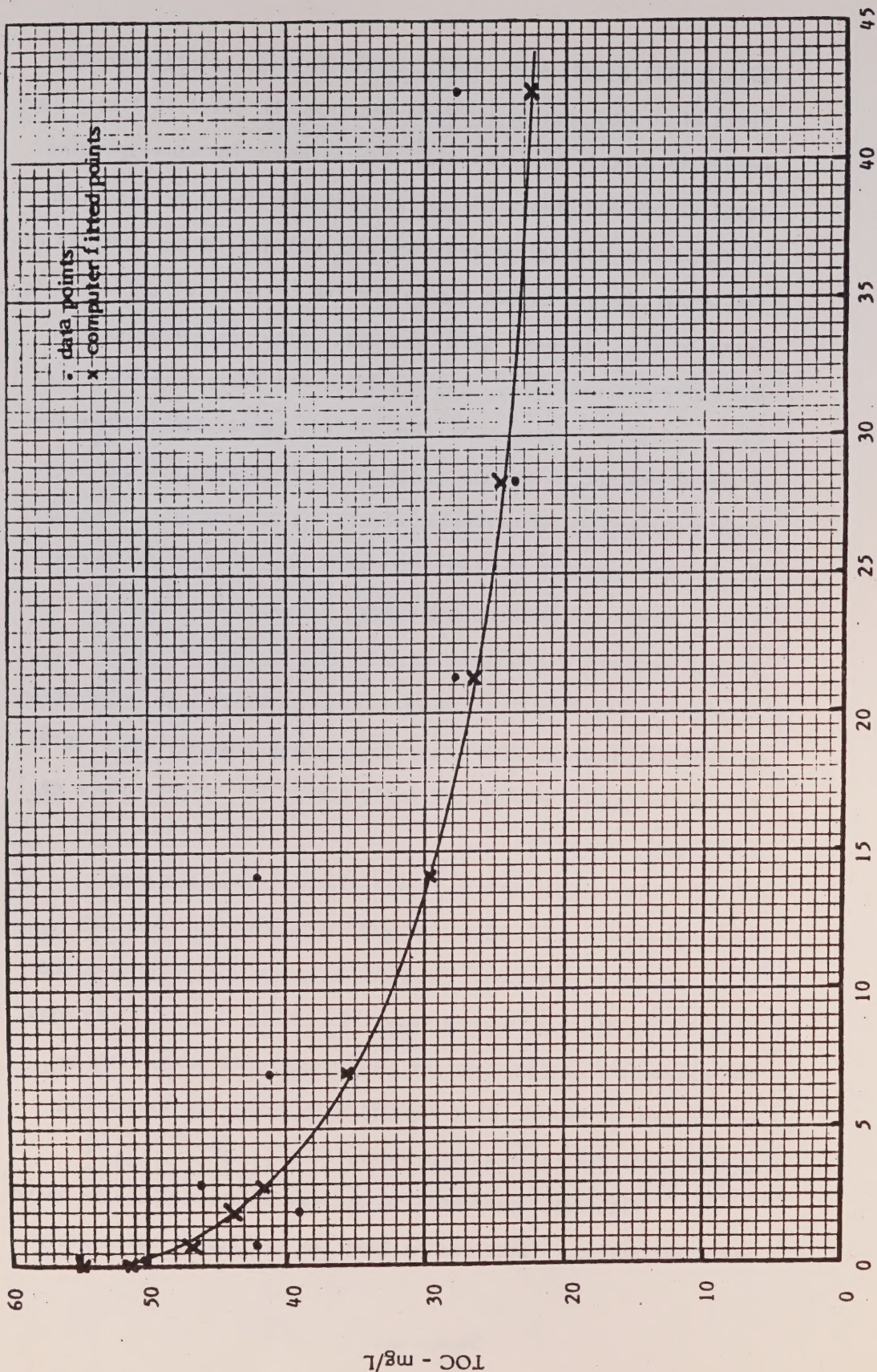
(CH₂ M Hill Canada Ltd., 1981). Nevertheless, an effluent TOC level of 10 mg/L can be achieved and this TOC level is likely low enough to satisfy environmental regulations. The corresponding level of oil and grease (hexane extractables) will be less than 10 mg/L. The removal of organics also eliminated the toxicity of the water. Before carbon adsorption the toxicity of the water in terms of EC₅₀ (15 min., 15°C) was 33%. After carbon adsorption the water was non-toxic. The result of the adsorption kinetics run is shown in Figure 3-26. The overall impression is that the organics present in the tar sands tailings supernatant are very slow in adsorbing on activated carbon (Filtrisorb 400). The indications are that the contactor will require long residence times. Numerical methods and ZENON's proprietary carbon adsorption model can be used to determine column design parameter. The computer simulation indicates that the adsorption is controlled by the very slow liquid phase transfer ($K_f = 10^{-5}$) around the carbon granules probably due to the acidic nature of the organic compounds.

The acidic nature of the organics may have been inferred from results of early tests by examining Table 3-2. Where the pH of the whole tar sands tailings was lowered to 4.6 from 7.7 the TOC was reduced from 179 mg/L to 19 mg/L along with the elimination of supernatant colour. Organic acids tend to precipitate at low pH, thus resulting in lower TOC levels and reduction of the color of the water.

Alternate adsorbents to activated carbon would be macro reticular resins. These resins have the ability to selectively

ACTIVATED CARBON ADSORPTION KINETICS

Carbon Dose: 21 mg F-400/100 mL



Elapsed Time - DAYS

adsorb a single class of compounds, thus improving the rate of adsorption. As the TOC in this water is probably largely composed of carboxylic acids the location and evaluation of a suitable resin would be advantageous.

3.6.3 Water Softening

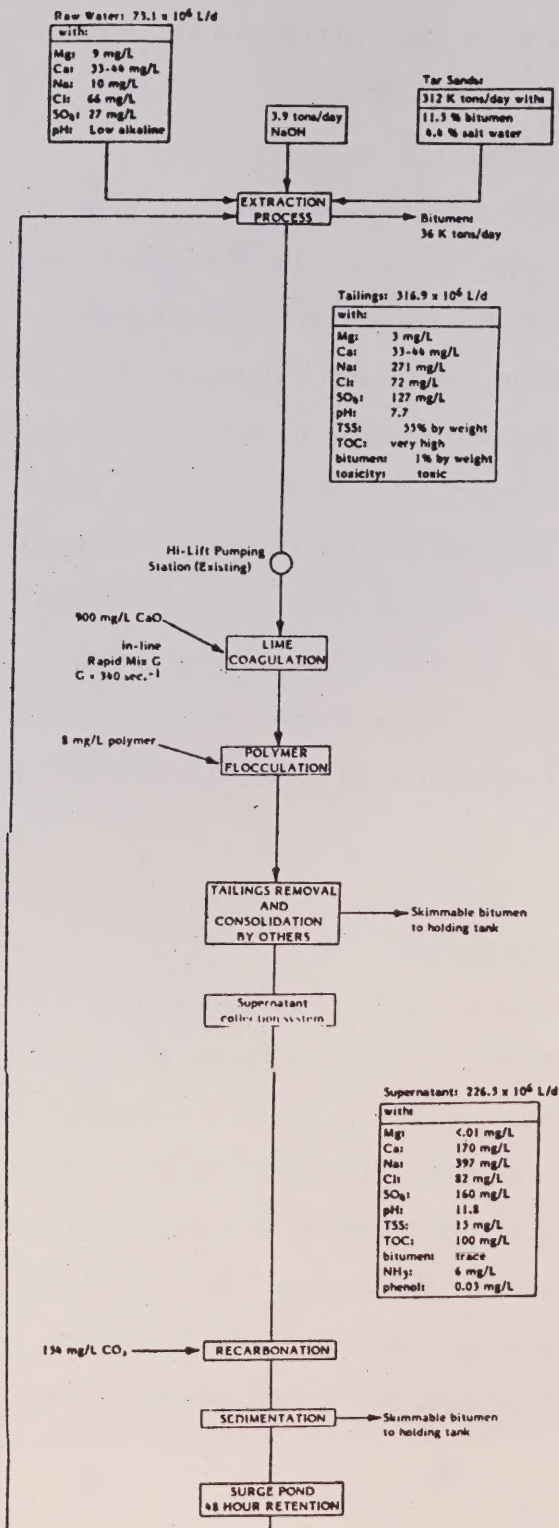
Oil field steam generators require feed water that contains less than 0.1 mg/L hardness, less than 1 mg/L insoluble oil, less than 8000 mg/L TDS and virtually no suspended solids. Coagulation, recarbonation with clarification, and filtration can produce a water that does not contain any insoluble oil or suspended solids. The removal of hardness relies on ion exchange water softening. Ion exchange water softeners are routinely used in oil field operations. A strong acid resin such as Amberlite IRA-120 will remove 1.07 eq of hardness per litre of resin with 20 lb NaCl per cubic feet of resin regeneration cycle. This resin treatment will reduce hardness to the levels required for boiler feed water.

3.7 Overall Process Design

The extensive experimental work carried out in this study guided the design of the process to treat the tar sands tailings in such a manner that the solids will settle and dewater easily, and that the water can be reused in the extraction process, can be used as oil field boiler feed water or can be discharged to surface water. A summary of the process with expected water flow rates and analysis is shown in Figure 3-27. The sizing of process equipment and design considerations to

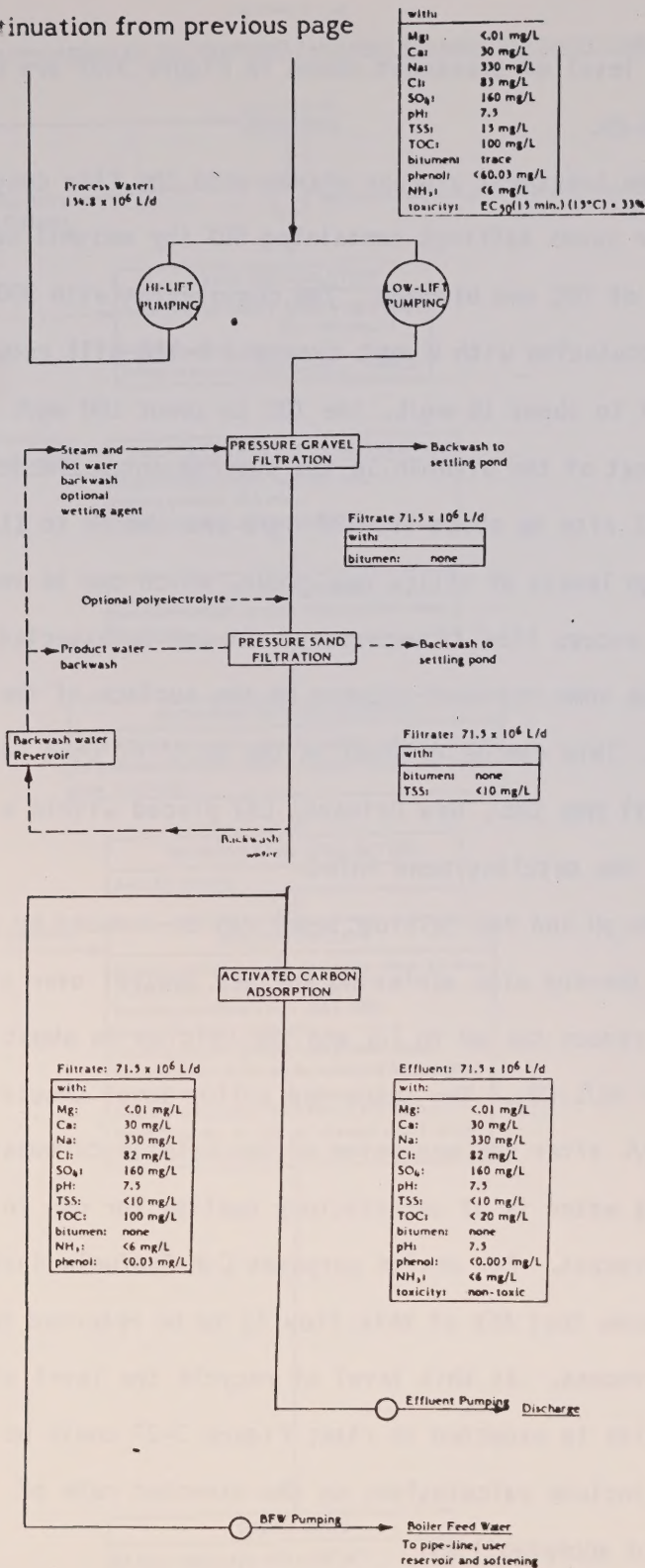
FIGURE 3-27

PROPOSED TAR SANDS TAILINGS
TREATMENT SCHEME AND ITS EXPECTED PERFORMANCE



Continued on next page

Continuation from previous page

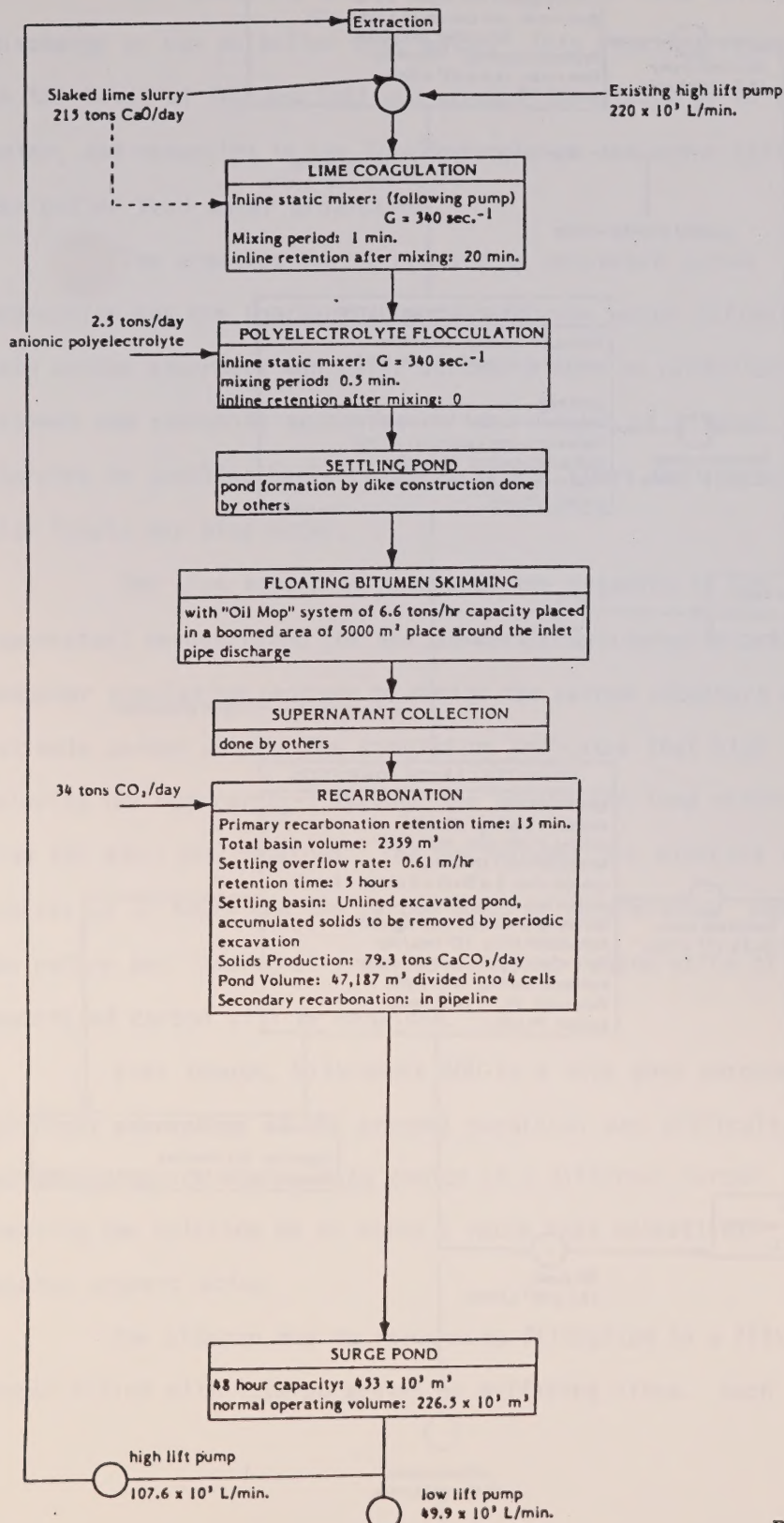


achieve the level of treatment shown in Figure 3-27 are presented in Figure 3-28.

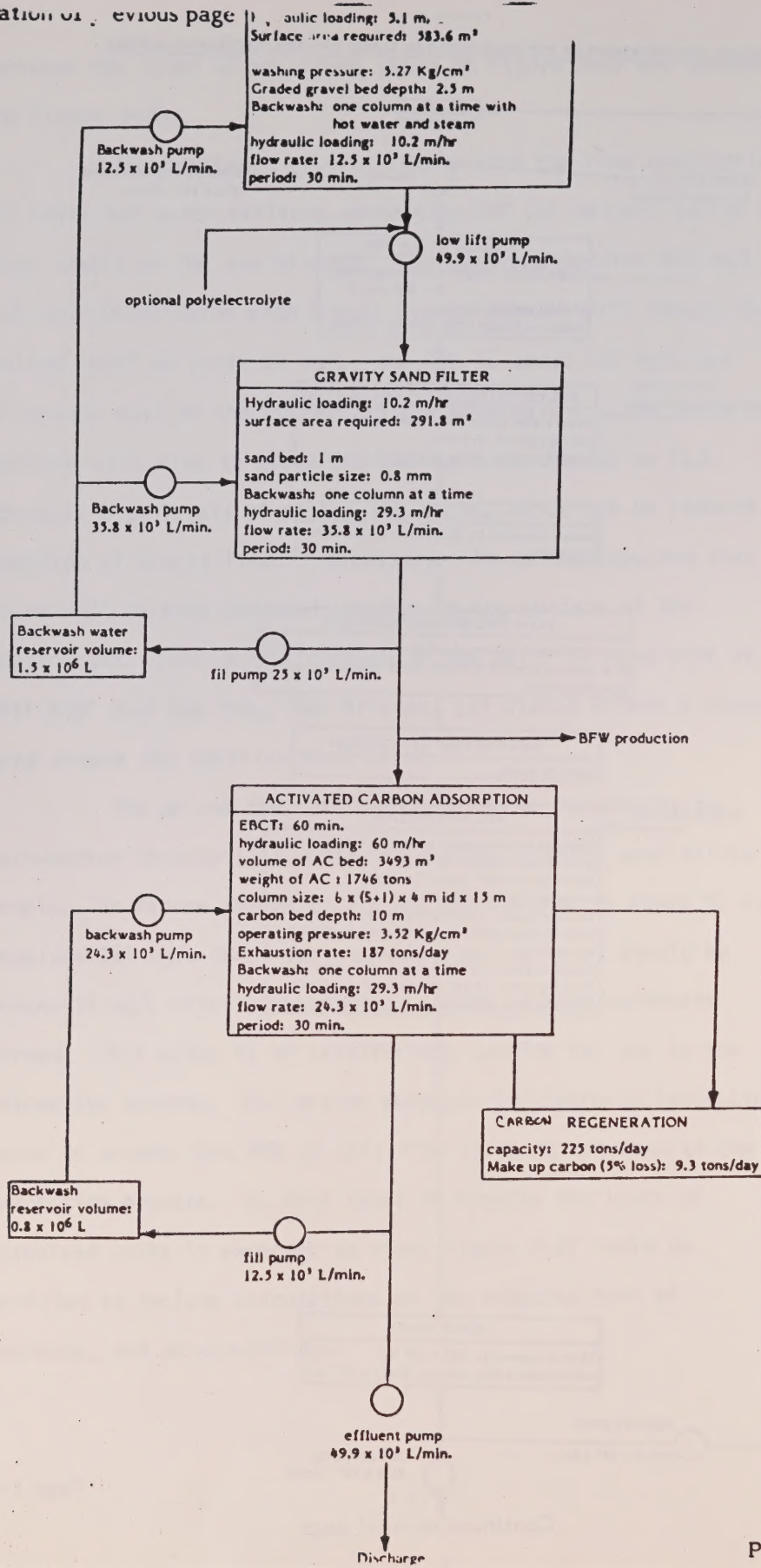
The treatment process starts with the lime coagulation of whole tar sands tailings containing 50% (by weight) solids and high levels of TOC and bitumen. The coagulation with 900 mg/L CaO and flocculation with 8 mg/L Cyanamid A-110 will reduce the solids level to about 15 mg/L, the TOC to about 100 mg/L and eliminate most of the bitumen in the supernatant. The level of calcium will rise to about 150-200 mg/L and the pH to 11.8. Sporadic high levels of silica may occur, which can be reduced by addition of excess lime if necessary. It can be expected that there will be some residual bitumen on the surface of the supernatant. This can be removed in the settling pond with an "Oil Mop" (Oil Mop Inc., New Orleans, LA) placed within a boomed area around the settling pond inlet.

The pH and the calcium level can be reduced by re-carbonation thereby also achieving further control over silica levels. To reduce the pH to 7.5 and the calcium to about 30 mg/L requires 154 mg/L CO₂. The suspended solids level should be around 15 mg/L after sedimentation of the calcium carbonate formed. This water is of satisfactory quality for use in the extraction process. For design purposes C-H Synfuels instructed Zenon to assume that 65% of this flow is to be returned to the extraction process. At this level of recycle the level of dissolved salts is expected to rise; Figure 3-27 could be modified to include calculations on the expected rate of increase, and acceptability.

DESIGN SPECIFICATIONS OF THE PROPOSED TAR SANDS TAILINGS TREATMENT SCHEME



Continued on next page



The remaining 35% of the flow must be made suitable for discharge or use as boiler feed water. This requires reduction in the level of TOC and "oil and grease" for discharge to surface water, and reduction in the level of calcium and other cations for boiler feed water production.

The organics can be removed by activated carbon adsorption and the inorganics by ion exchange water softening. Both carbon adsorbers and water softeners must be protected from bitumen and excessive suspended solids. Traces of bitumen can be expected in settling basin overflow at all times and sporadic high levels may also occur.

The slow adsorbing nature of the organics in the supernatant necessitated the use of the Zenon's proprietary computer simulation program to design the carbon adsorbers and to estimate carbon usage. The simulation indicates that high liquid velocity (60 meters/hour) through the column and long retention time (60 min.) are required. The bed volumes are expected to exhaust in 32 hours and the carbon must be regenerated. Due to the nature and loading of organics frequent regeneration of large amounts of carbon will be required.

Even though, Filtrasorb 400 is a very good adsorbent, efficient adsorption at the present condition was difficult. Adsorption may be improved by choice of a different carbon lowering the solution pH or using a resin that selectively adsorbs organic acids.

The bitumen may be removed by filtration in a filter vessel filled with layered gravel of differing sizes. Such

filters are commonly used in the iron and steel industry for removal of tars from phenolic coke oven wastewaters. The smallest gravel is at the bottom and the largest in the top. The bitumen can be removed from the gravel with hot water backwash and steam scour. The backwash water can be returned to the extraction process. A crushed coke bed is a further possibility and could be regenerated with hot alkaline water. Conventional sand filters can be used to remove suspended solids and turbidity after gravel filtration. By these means the bitumen will be eliminated and the level of suspended solids will be substantially below 10 mg/L.

For production of boiler feed water a sodium cycle ion exchange water softener will reduce water hardness to levels acceptable for oil field steam generators.

The concentration of dissolved organics must be reduced. Granular activated carbon contactors will reduce the TOC of the water to as low as 10 mg/L and eliminate the toxicity of the water. The upper limit of TOC is subject to negotiations with regulatory authorities. The inorganic constituents of the carbon treated water are within the usual range.

4.0 CONCLUSIONS

1. Whole tar sands tailings can be coagulated with lime to produce a rapidly-settling solid phase and clear supernatant. Optimum dosage of lime is in the range of 800-900 mg/L as CaO, optimum G rate is about 340 sec^{-1} and rapid mix time in the range of 20 to 30 minutes. Settling rate and separation of bitumen are enhanced at higher temperature (69°C) when compared with room temperature.
2. Addition of an ionic polyelectrolyte at a dosage rate of 6 to 8 mg/L at the end of the rapid mix period greatly accelerates settling rate, reduces sand clay stratification in the settled solids and produces a more compact solids phase than can be obtained by settling untreated whole tails or tailings coagulated with lime alone.
3. Unconfined compressive strength, thermal and X-ray diffraction analysis results, all indicate that pozzolanic reactions did not take place in the lime treated whole tar sands sediment.
4. Microtox determination of supernatant toxicity indicated that the raw tar sands tailings supernatant was toxic, the lime treated tar sands tailings supernatant was less toxic and the activated carbon treated supernatant was non-toxic.

5. Recarbonation and settling of the lime-coagulated supernatant to pH 7.5 or below removes excess dissolved calcium and silica, resulting in a water suitable for recycle to the extraction process.
6. Recarbonated water may be upgraded to produce a water suitable for boiler feed in once-through oil-field steam generators. The necessary treatment consists of gravel and fine sand filtration for removal of bitumen and turbidity, and IX resin softening for removal of calcium.
7. Recarbonated water may be treated to produce a water suitable for surface discharge. Treatment consists of gravel and fine sand filtration followed by carbon adsorption for removal of hexane extractables and total organic carbon.

5.0 RECOMMENDATIONS

1. Recycle and re-use of a higher portion of the tailings water should be investigated, to reduce the quantity requiring disposal.
2. Alternative adsorbents to Filtrasorb 400 carbon should be investigated at bench-scale.
3. Further bench-scale work be conducted to evaluate freeze - thaw stability and leachate characteristics of the lime coagulated material.
4. Pilot-scale work should be initiated to firm up water-treatment system design parameters and process operating costs, and to confirm suitability of the treated waters for recycle, boiler feed and discharge.

ACKNOWLEDGEMENTS

This report was prepared by ZENON Environmental Inc. with helpful inputs and comments from C-H Synfuels, Ltd. and the Scientific Authority for Environment Canada, Wayne Richardson.

Special thanks to the staff of the Water Treatment Centre, Burlington, in particular to Trevor Bridle for their advice and assistance in defining the products of lime coagulation.

REFERENCES

1. CH₂M Hill Can. Ltd. (1981). Review of Treatment and Recycling of Produced Water from Heavy Oil Fields.
2. Hesse, P.R. (1971). A Treatment of Soil Chemical Analysis. Chemical Publishing Co., Inc. New York.
3. Mattson, J.S. and Mark, H.B. (1971). Activated Carbon Surface Chemistry and Adsorption from Solution. Marcel Dekker Inc., New York 1971.
4. Standard Methods for the Examination of Waste and Wastewater, APHA, AWWA, WPCF (1971).

APPENDIX A

Report No. X84006

X-Ray Analysis of Tar Sand Tailings

for

ZENON Environmental Inc.

845 Harrington Court

Burlington, Ontario

L7N 3P3

Attention: Mr. John Bancsi

E. NISKANEN, P.ENG.

MATERIALS DIVISION

17TH JANUARY, 1984.

January 17, 1984

Zenon Environmental Inc.
845 Harrington Court
Burlington, Ontario
L7N 3P3

Attention: Mr. John Bancsi

Dear Sir:

Report No.X84006
X-Ray Analysis of Tar Sand Tailings

Three samples of tar sand tailings have been analysed by x-ray diffraction to determine whether any mineralogical changes have taken place after treatment with lime. The original raw material was also analysed by semi-quantitative x-ray fluorescence spectrography to determine its overall elemental composition.

The samples were labelled as follows:

Sample R - original raw material
Sample S - treated with <0.5% lime
Sample P - treated with ≈10% lime

Prior to any analytical work, each sample was screened at 100 mesh to remove some of the coarser sand. The fine fraction (-100#) was used for all analytical work.

X-Ray Diffraction Results

Copies of the XRD patterns are shown in Figures 1 to 3. The major component in each sample is quartz, SiO_2 . Minor components present in each sample include a feldspar mineral (probably microcline KAlSi_3O_8), and two clay minerals (illite and kaolin). An unidentified minor component is also

.../2

present in all three samples. The only significant difference in mineralogical composition is the presence of calcium hydroxide Ca(OH)_2 and calcium carbonate CaCO_3 in Sample P.

	<u>Sample R</u>	<u>Sample S</u>	<u>Sample P</u>
Quartz	major	major	major
Feldspar	minor	minor	minor
Illite	minor	minor	minor
Kaolin	minor	minor	minor
Ca(OH)_2	-	-	minor
CaCO_3	-	-	minor

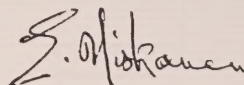
X-Ray Spectrographic Results

Detailed results of the spectrographic scan are given on the attached report form.

Conclusions

Treatment with lime has not altered the mineralogical composition of a tar sands tailing material, to the extent determinable by x-ray diffraction.

Yours truly,



E. Niskanen, P.Eng.
X-Ray Specialist
Materials Division

:lu

SEMI-QUANTITATIVE X-RAY SPECTROGRAPHIC ANALYSIS

SHERIDAN PARK RESEARCH COMMUNITY

MISSISSAUGA, ONTARIO, CANADA L5K 1B3 • (416) 822-4111 • TELETYPE 982311

Zenon Environmental Inc. 845 Harrington Court Burlington, Ontario L7N 3P3 Attention: Mr. John Bancsi	Sample Description: Sample R Order No.:
--	---

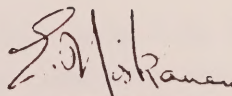
A search was made for all elements with atomic number greater than 8. Approximate values (weight %) are given below for all elements detected. Elements with a blank entry and elements not listed were not detected in the sample.

11	Sodium	0.1
12	Magnesium	0.2
13	Aluminum	3
14	Silicon	High
15	Phosphorus	
16	Sulphur	0.1
17	Chlorine	0.01
19	Potassium	0.8
20	Calcium	0.07
22	Titanium	0.3
23	Vanadium	
24	Chromium	
25	Manganese	0.03
26	Iron	0.7
27	Cobalt	

28	Nickel	0.005
29	Copper	0.007
30	Zinc	
33	Arsenic	
35	Bromine	
38	Strontium	0.004
40	Zirconium	0.01
41	Niobium	
42	Molybdenum	
47	Silver	
50	Tin	
51	Antimony	
56	Barium	
74	Tungsten	
82	Lead	

37	Rubidium	0.002

Date: January 17, 1984



E. Niskanen, P.Eng.
Materials Division.

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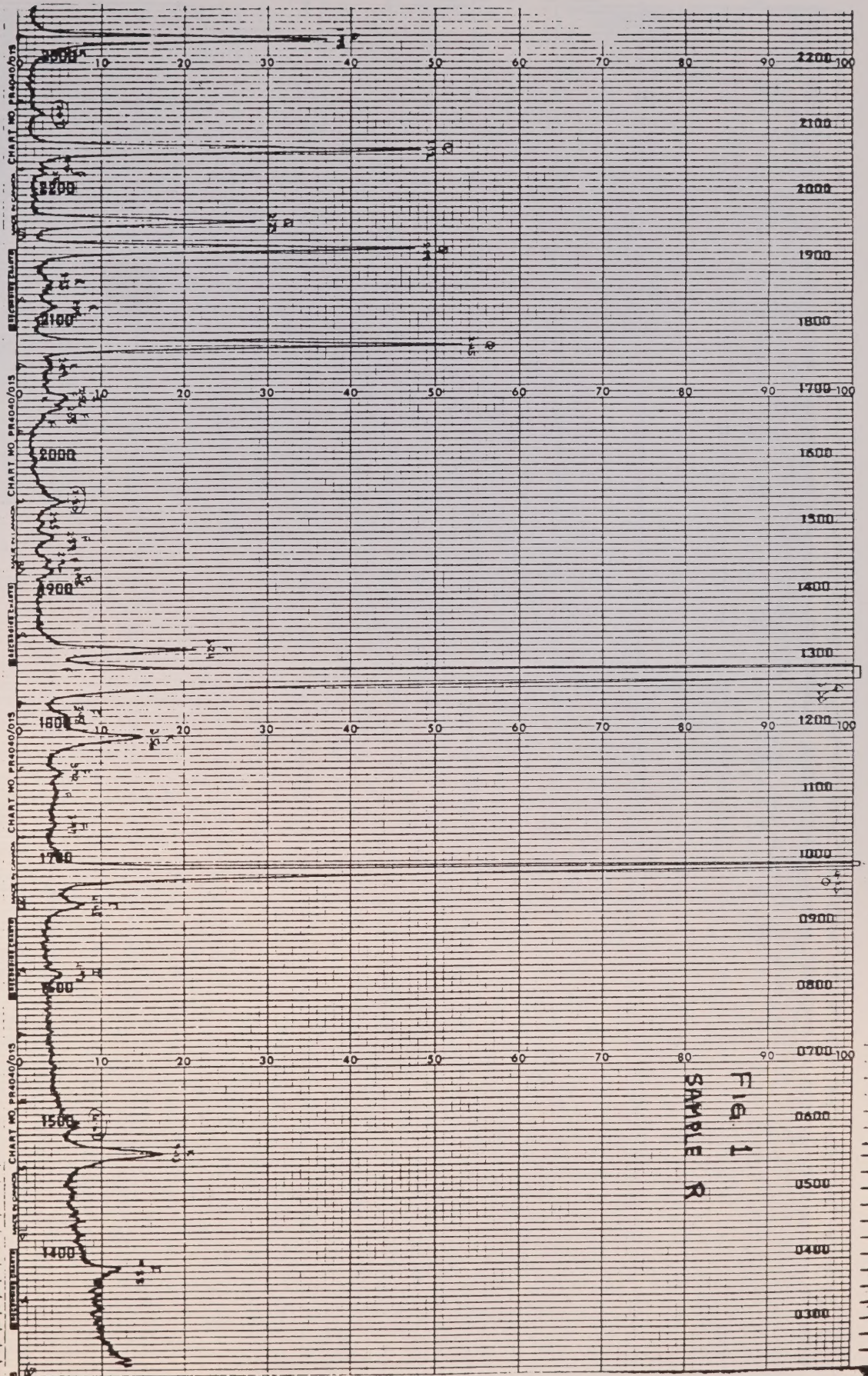


FIG. 1
SAMPLE R

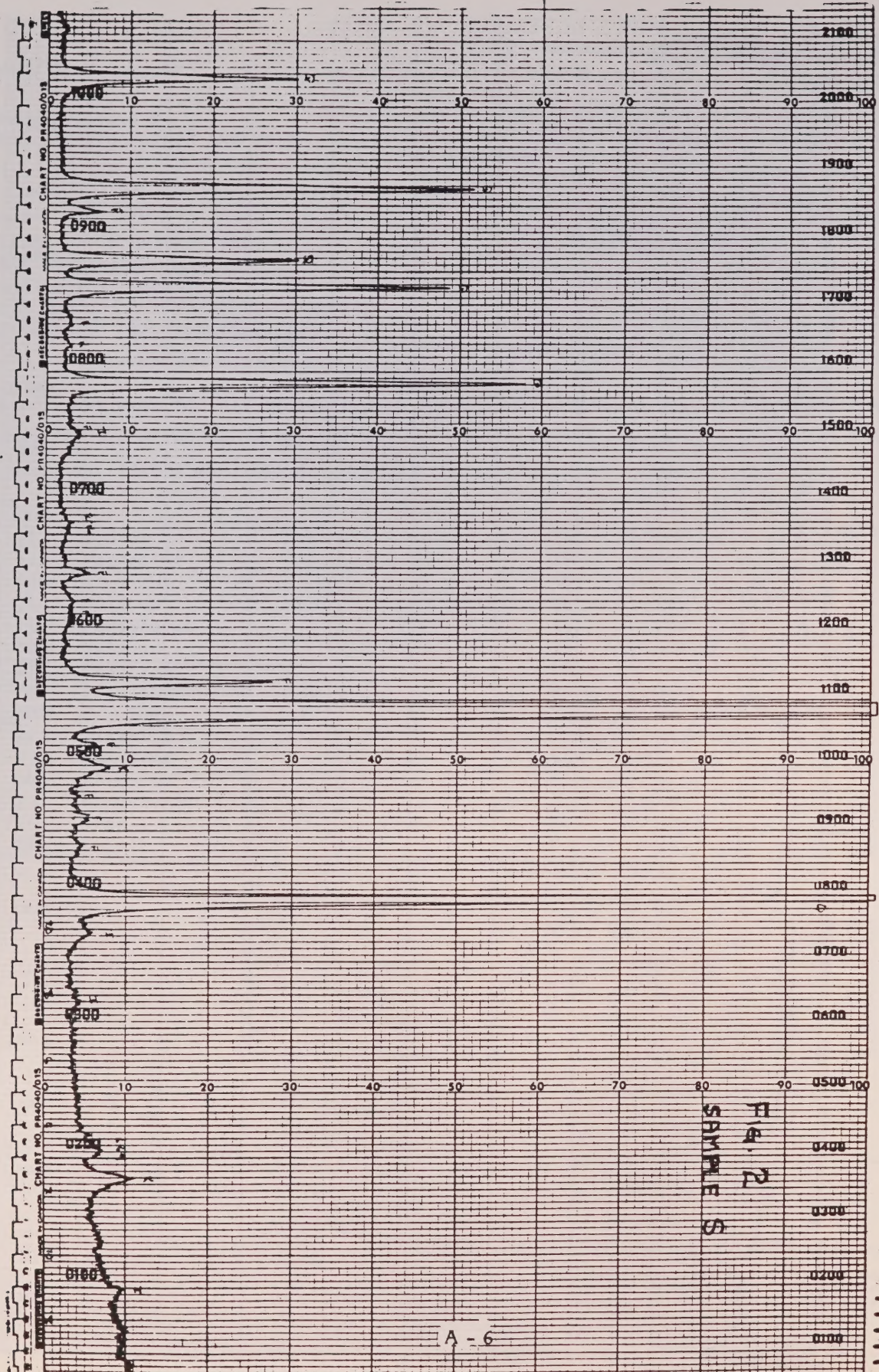


FIG. 2
SAMPLE S

CCCC

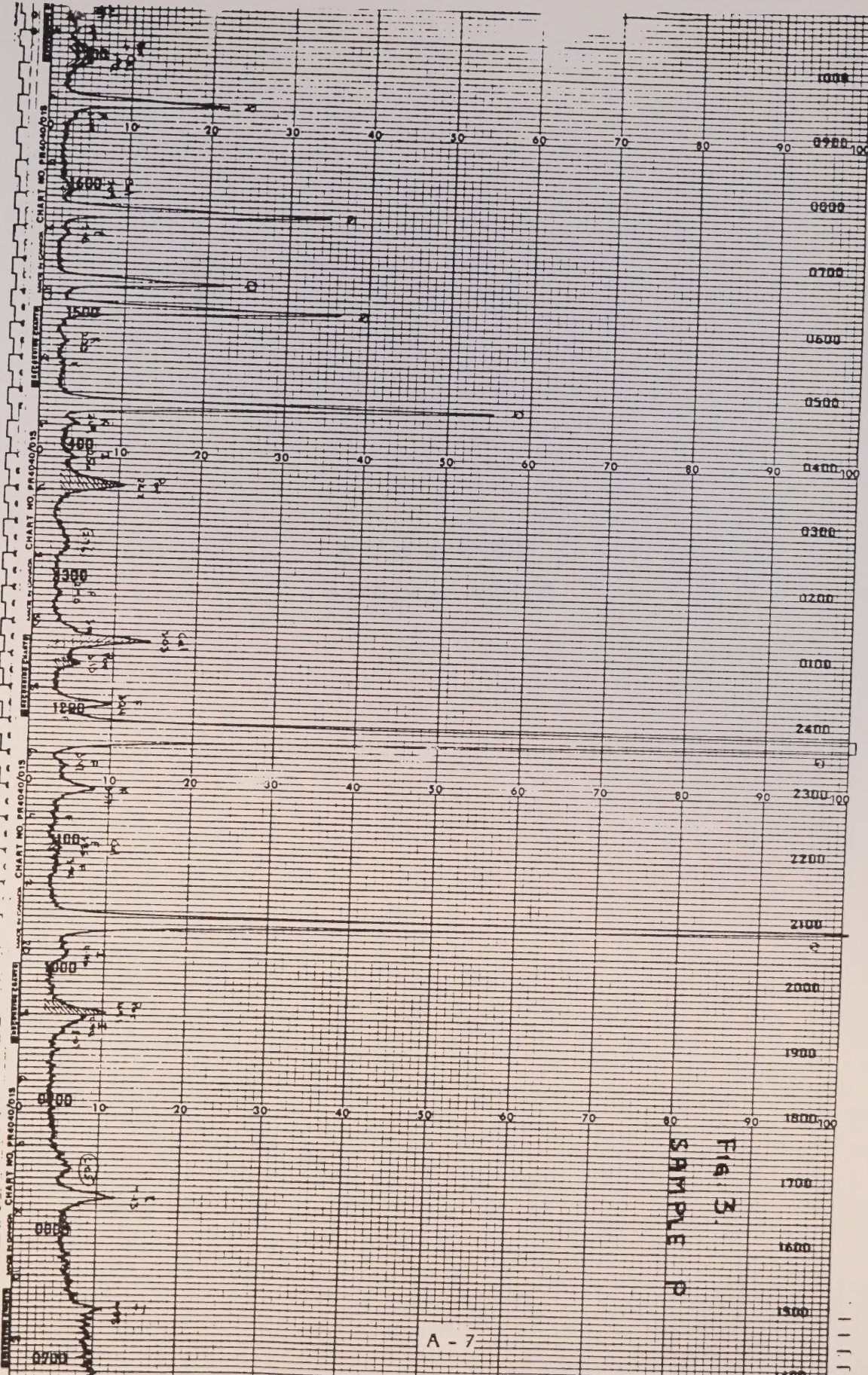


FIG. 3.
SAMPLE P

RESULTS OF THERMAL DIFFERENTIAL ANALYSIS

SAMPLE IDENTITY FOR TDA ANALYSIS

<u>Sample No.</u>	<u>Sample Identity</u>
R	Untreated and evaporated whole tar sands tailings.
L	Sediment of 900 mg/L CaO coagulated whole tar sands tailings.
L+P	Sediment of 900 mg/L CaO coagulated and 8 mg/L polyelectrolyte flocculated whole tar sands tailings.
High Lime + High Temp.	Sediment of 3000 mg/L CaO coagulated whole tar sands tailings. Coagulation was carried out at 69°C.
900	Sediment of 900 mg/L CaO coagulated whole tar sands tailings. Curved for 158 days.
0.1%	Untreated and evaporated whole tar sands tailings with CaO added to make up 0.1% of solids by weight. Curved for 158 days.
3%	Untreated and evaporated whole tar sands tailings with CaO added to make up 3% of the solids by weight. Curved for 158 days.
10%	Untreated and evaporated whole tar sands tailings with CaO added to make up 10% of the solids by weight. Curved for 158 days.



Environment
Canada

Environnement
Canada

Environmental
Protection

Protection de
l'environnement

Wastewater Technology Centre,
P.O. Box 5050,
Burlington, Ontario. L7R 4A6

December 19, 1983

DEC 20 1983

Your file Votre référence

Our file Notre référence

37

Mr. T. Tonelli
Zenon Environmental Enterprises Ltd.
845 Harrington Court
Burlington, Ontario L7N 3P3

Dear Tony:

As discussed on December 16th, the Thermal Analyser is currently in need of repair and, as a result, we have not run the four additional tar sand samples you provided us. However, as soon as the instrument is up and running, we will process these samples. The preliminary results generated from the March '83 samples are attached for your information. Samples R, L, L+P and High Lime + High Temp. were analyzed.

Sample R (raw waste?) shows a 2% weight loss to 460°C (Figure 1). Sample L (Lime addition?) exhibited potential endotherms at 570°C, 725°C and 790°C (Figure 2) and a weight loss of 1.5% to 1075°C (Figure 3). The 570°C endotherm could be due to the dehydration of lime, which is reported to occur between 550°C and 580°C. The 725°C and 790°C endotherms are of unknown origin. The fact that a weight loss of only 1.5% is evident up to 1075°C indicates very low potential concentration of lime or calcium carbonate. Sample L+P (Lime + polymer?) exhibited an endotherm at 860°C and a weight loss of 1% at a temperature of 530°C. The endotherm could be due to CO₂ evolution from calcium carbonate (reported to occur at 825°C, aragonite). The high lime plus high temperature sample exhibited no measurable thermal response to 900°C (Figure 6).

In summary, the results generated to date do not provide any substantial evidence that pozzolanic reactions have occurred. Sample L+P does indicate carbonation of lime has taken place, albeit at low concentration.

I hope these preliminary results are of some value to you and, as promised, we will run the new samples as soon as the TA is repaired.

Regards,

T.R.B.

T.R. Bridle

Att.

Canada

Sample: R

Size: 50.22 mg

Rate: 20 mL/min

Date: 28-Mar-83

File: ZENON.04

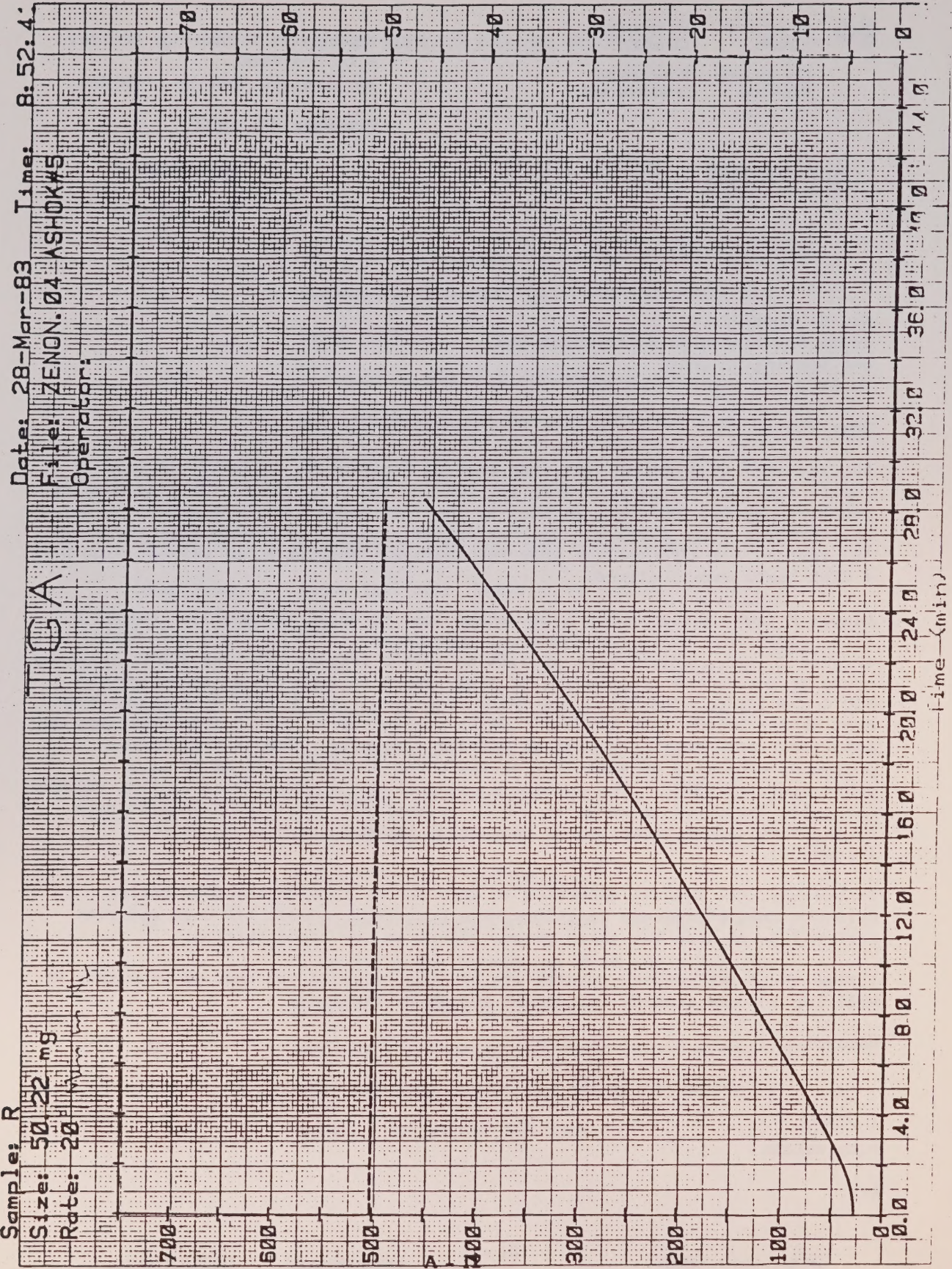
Operator:

Time: 8:52:41

TGA

[—] Temperature (°C)

Time (min)



Sample: L

Size:

Rate: 20 °C/min

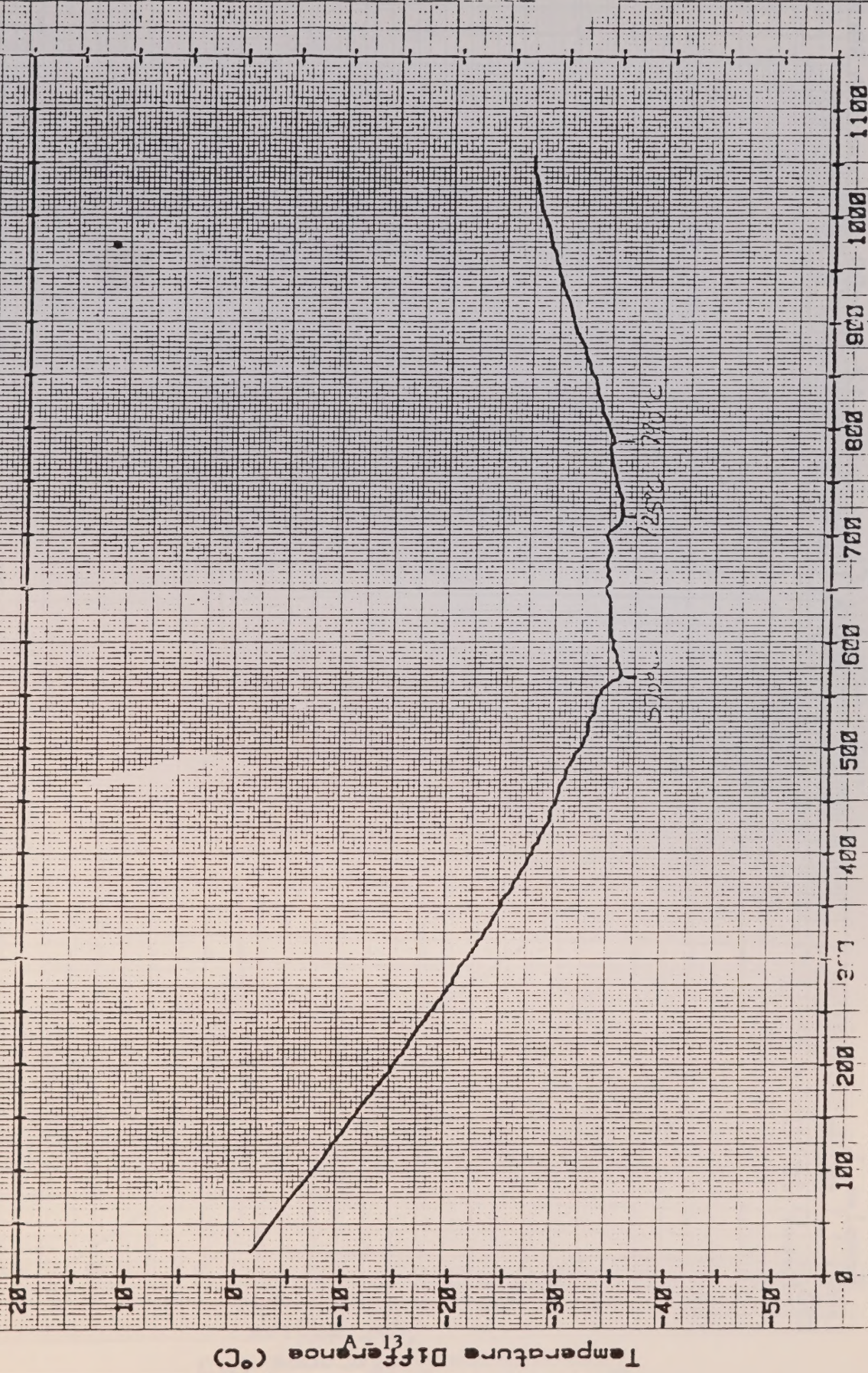
DTA

Date: 15-Apr-83

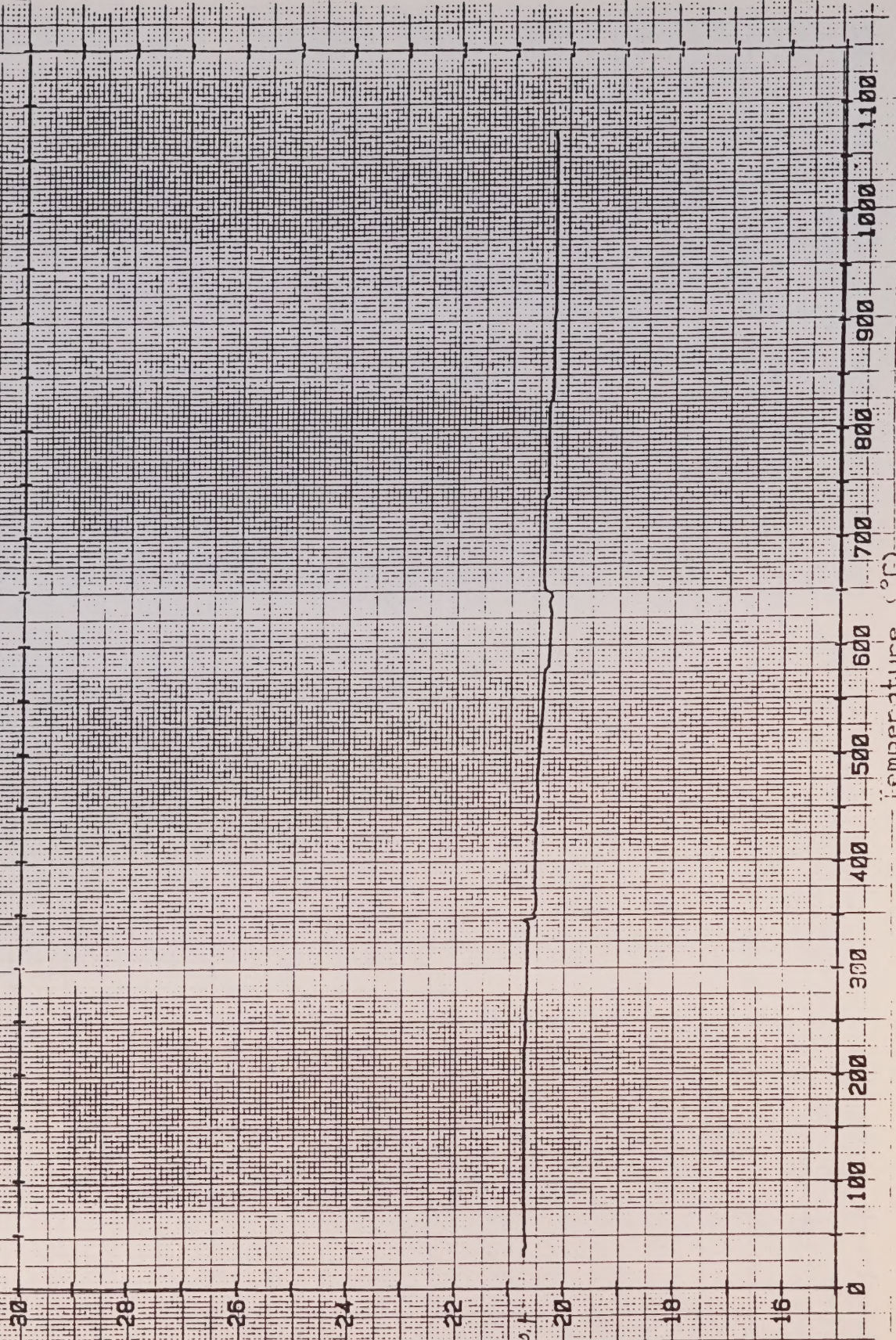
File: ZENON.14-ASHOK#5

Operator:

Time: 10:21:02



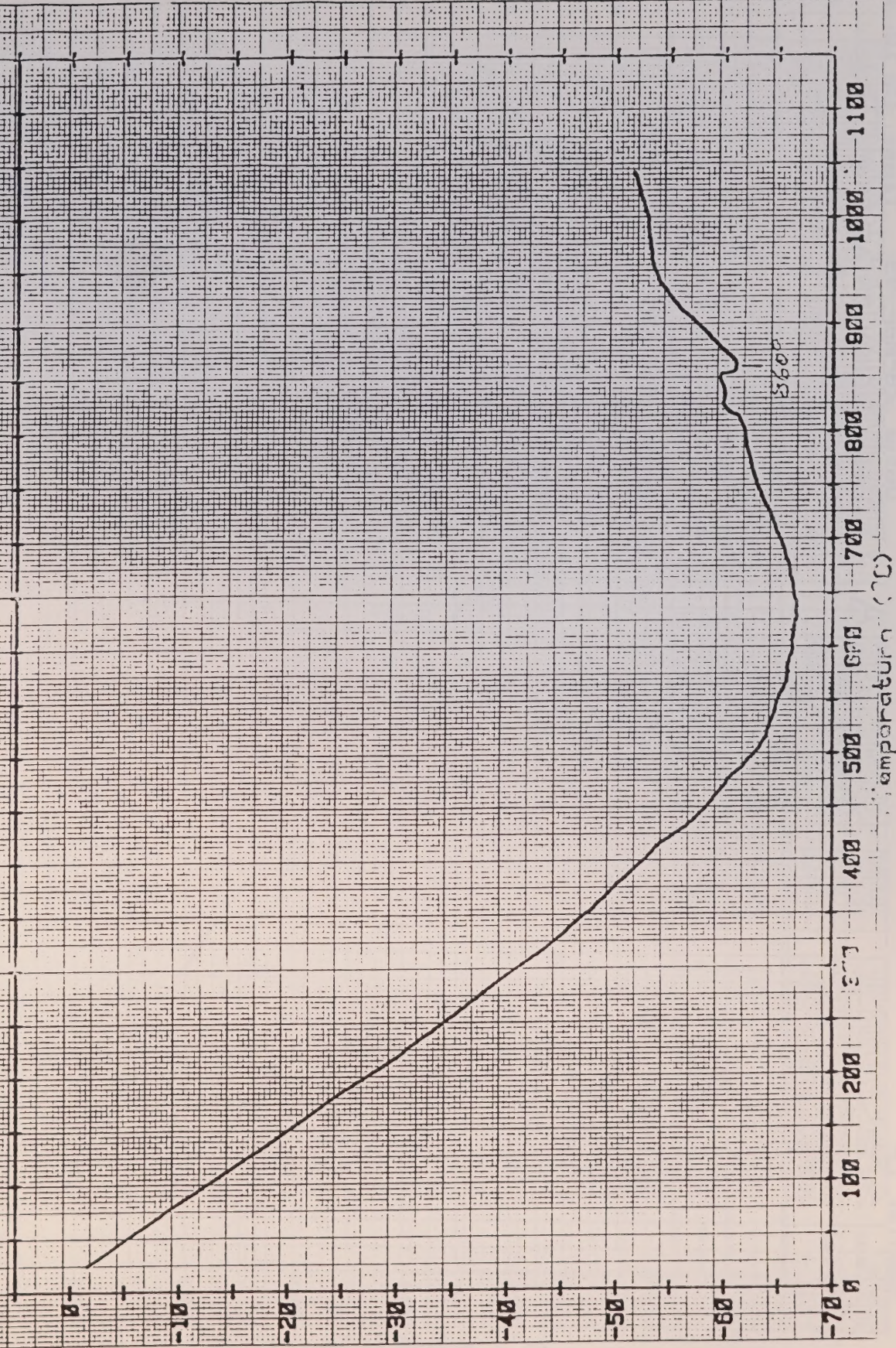
Sample: TGA
Size: 20.72 mg
Rate: 20/MIN AIR
Date: 12-Apr-83 Time: 9:38:01
File: ZENON.10 ASHOKA5
Operator:



Sample: L+P
Size:
Rate: 20 pc/min - Nz

DTA

Date: 14-Apr-83 Time: 10:17:31
File: ZENON.13 ASHOK#5
Operator:



Sample: LP

Size: 26.30 mg

Rate: 20 ml/min

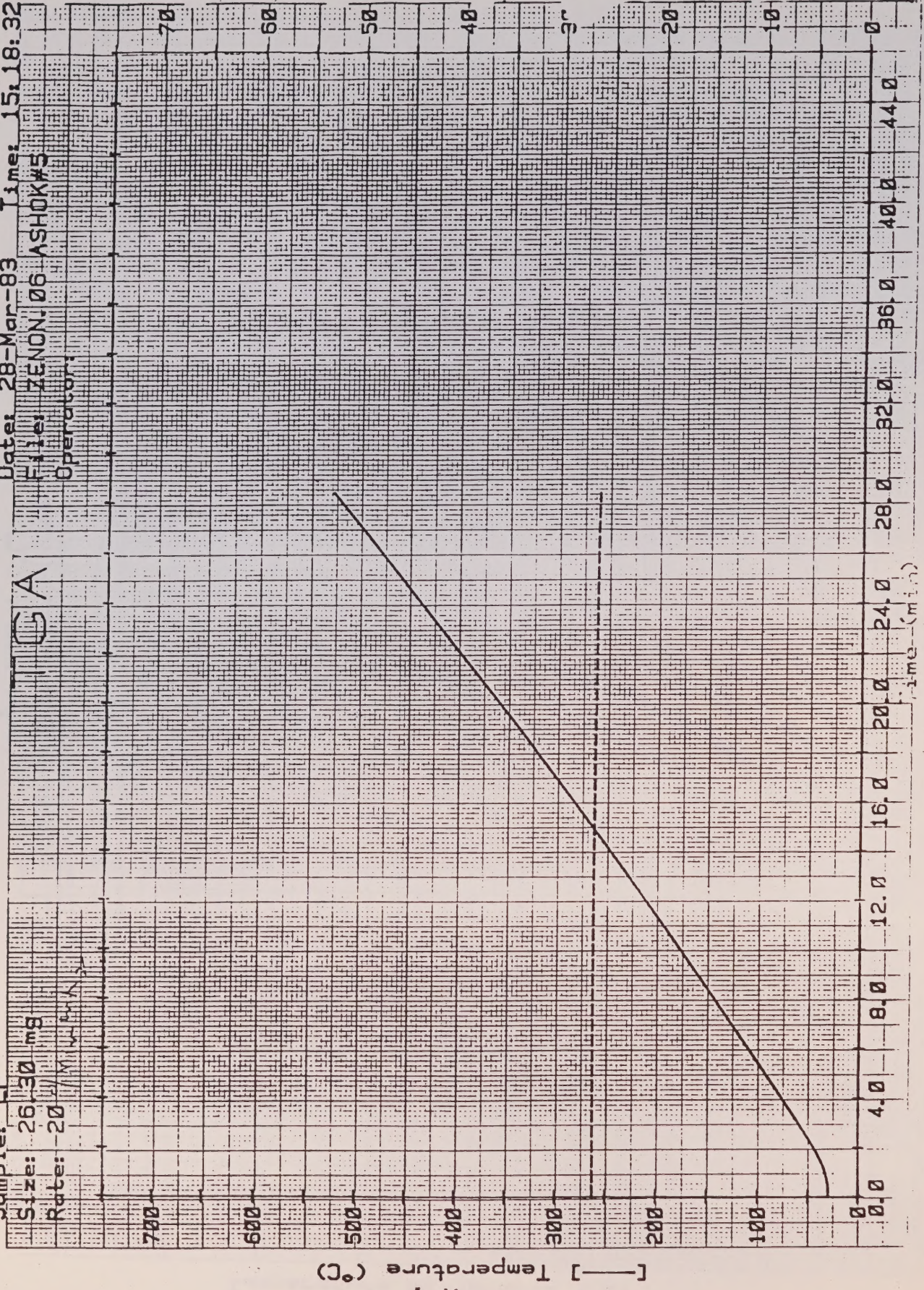
TGA

Date: 28-Mar-83

File: ZENON.06 ASHOK#5

Operator:

Time: 15:18:32



五

Rate: 20/MIN AIR

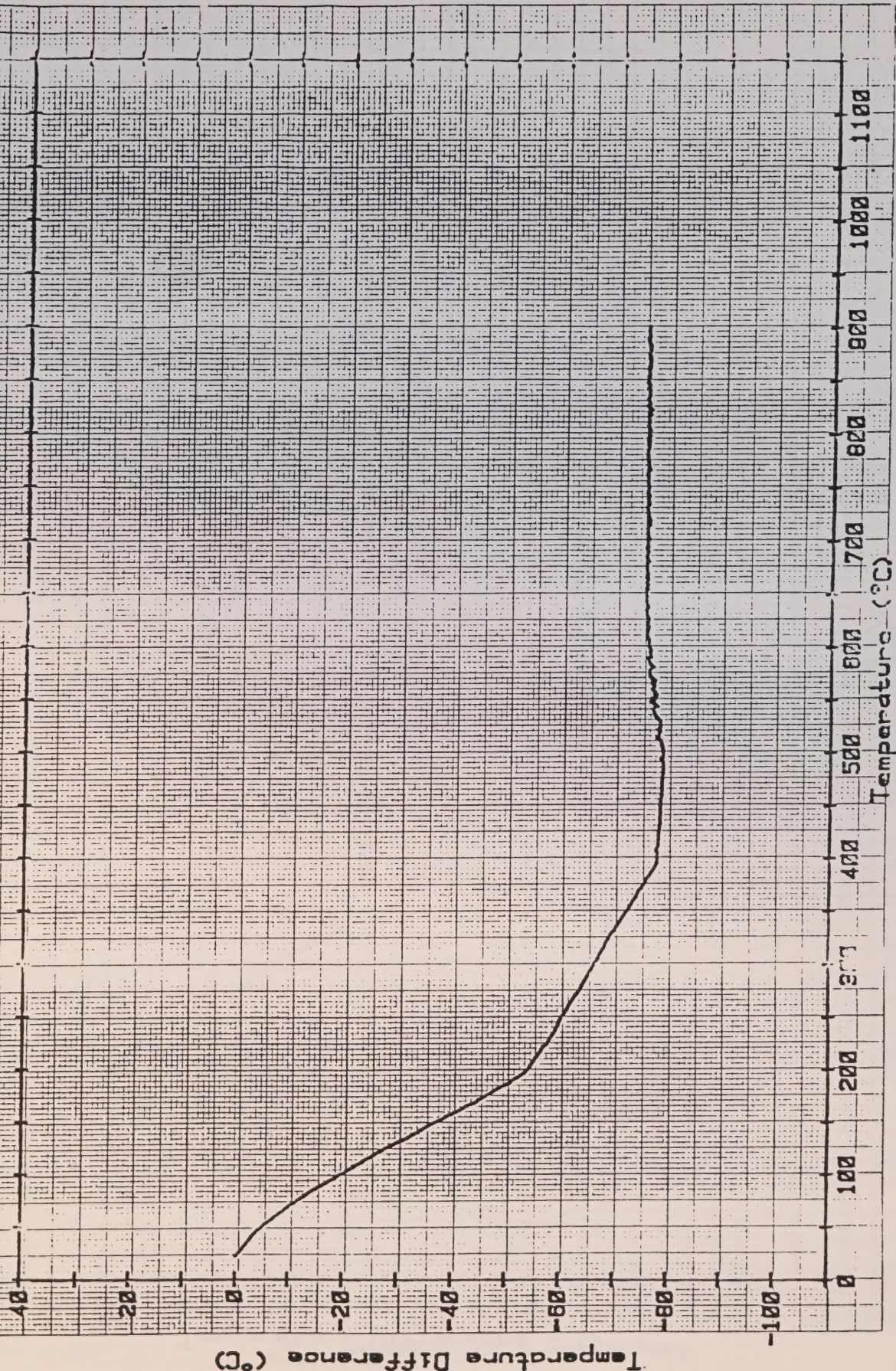
卷一百一十五

File: ZENON.17 ASHOK#5

Deborah

Date: 19-Apr-83

Time 9:20:42



Sample: 900

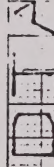
Size: -----

Rate: 20/MIN

Date: 22-Feb-84 Time: 8:53:38

File: ZENON.04 AS#1

Operator: AKS



Temperature Difference (°C)

Temperature (°C)

Sample: 0.1%
Size: ----
Rate: 20/MIN

Date: 21-Feb-84 Time: 8:58:43
File: ZENON.02 AS#1
Operator: AKS

D T A

0.6

0.4

0.2

0.0

-0.2

-0.4

-0.6

-0.8

Temperature Difference (°C)

Temperature (°C)

1100

1000

900

800

700

600

500

400

300

200

100

0

$\alpha \rightarrow \beta$ quartz

Sample: 3X

Size: -----

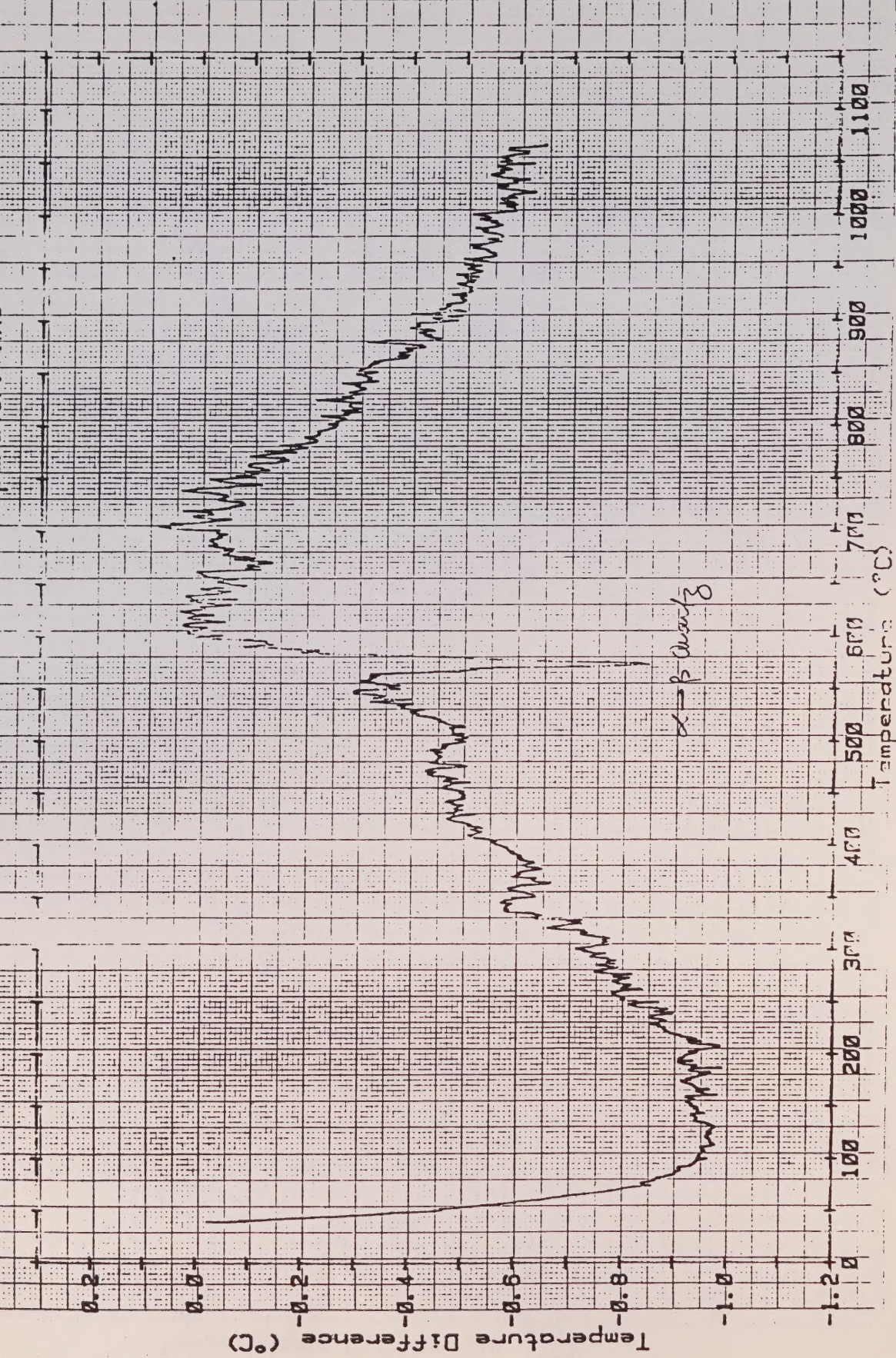
Rate: 20/MIN

Date: 21-Feb-84 Time: 13:08:37

File: ZENON.03 AS#1

Operator: AKS

D A



Sample: 10%

Size: -----

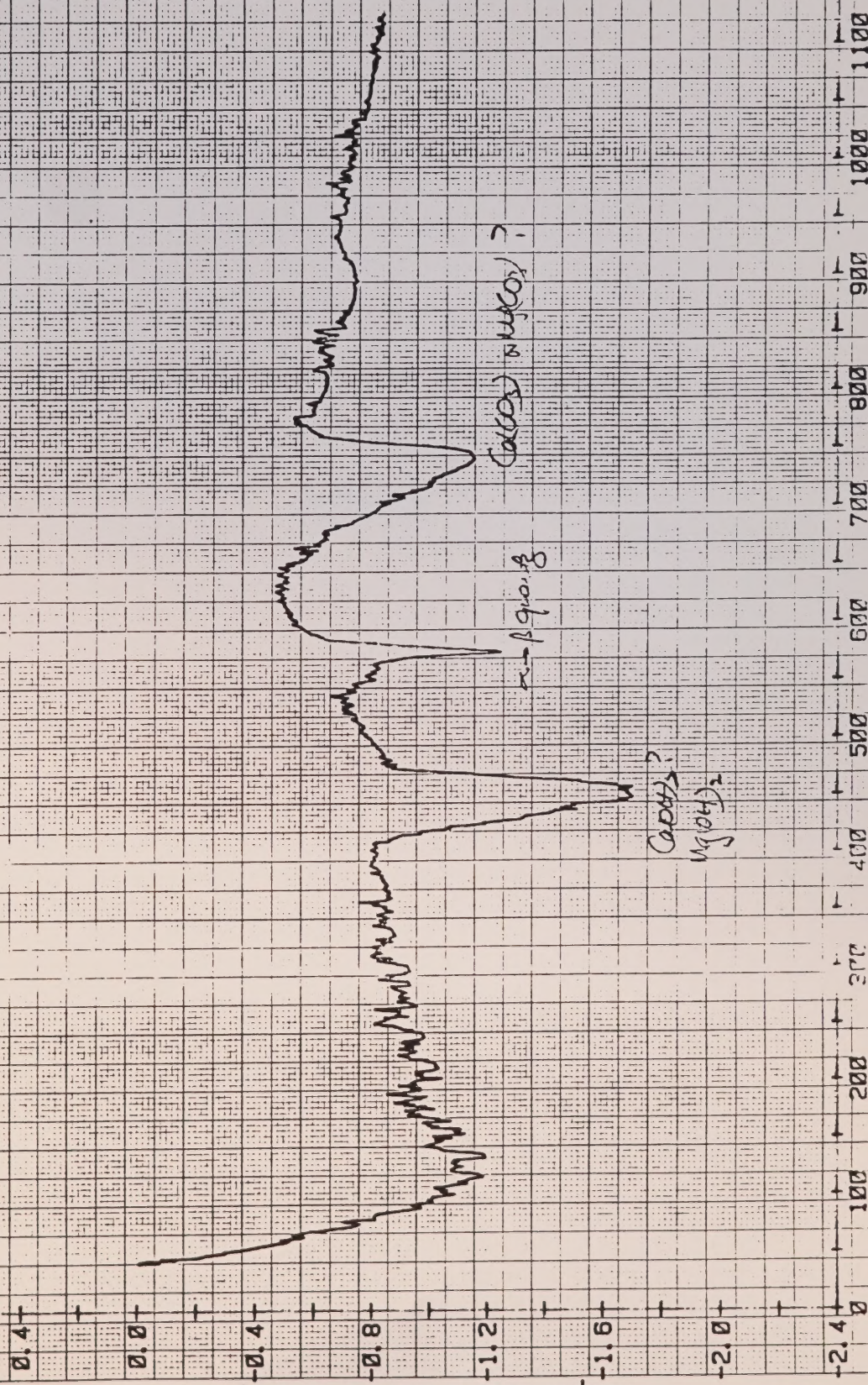
Rate: 20/MIN

Date: 2

DTA

Temperature Difference (°C)

Temperature (°C)



APPENDIX B

COSTING OF THE PROPOSED
WHOLE TAR SANDS TAILINGS
TREATMENT FACILITY

The cost of the process shown in Figure 3-28, was estimated. The purpose of the process is to separate the liquid and solids fraction of the whole tar sands tailings, to treat the water for re-use in the extraction process, and to treat the balance of the water to enable discharge to a body of surface water or to be used as feed water to once through boilers. The costs were based on EPA (1979) and converted to current Canadian monetary values.

The costing excluded the existing high lift pumps, high lift pumps to return water to process, pumps to move the water to boiler feed water treatment facilities and pump to discharge any excess water. Costing also excluded pond construction and supernatant collection systems.

The costing was divided into three categories: construction (capital) cost, annual operation and maintenance cost and annual chemical cost.

The construction cost includes (where applicable)

- i) excavation and site work directly related to process,
- ii) manufactured equipment and accessories that are factory made and sold with the equipment,
- iii) concrete (delivered ready-mix), and concrete forming materials,

- iv) steel for concrete reinforcing and steel not included within manufactured equipment,
- v) labor associated with installing manufactured equipment, piping and valves and site work,
- vi) pipe and valves not included within manufactured equipment,
- vii) electrical equipment and instrumentation, wiring and general instrumentation associated with process equipment,
- viii) housing required for process equipment, and,
- ix) contingency of 15 % of the above sum.

Initial charge of activated carbon was included under capital cost and listed separately.

Operation and maintenance cost includes the cost of:

- i) energy required to operate the process and related equipment,
- ii) routine maintenance materials and,
- iii) the labor required for routine maintenance.

The cost of chemicals were developed from current charges by suppliers for on site production, or FOB price at the nearest depot.

The cost of the major subcomponents of the whole tar sands tailings treatment facility, as shown in Figure 3-28, is listed in Table B-1.

With the exception of the activated carbon treatment the costs are considered to be reasonable. The difficult to adsorb nature of the organics dominates the high cost (2/3 of the total) of activated carbon treatment and carbon regeneration. In the light of this high cost, methods of reducing the volume of water treated, and alternate treatment process (ie. reverse osmosis) or an alternate adsorbent (ie. macroreticular resin) should be sought. An optimized carbon adsorption system using non-thermal methods of regeneration should also be investigated.

TABLE B-1

COSTS OF THE MAJOR SUBCOMPONENTS OF THE TREATMENT FACILITY OUTLINED IN FIGURE 2 28

Equipment or Initial fill	Construction \$	O & M \$/year	Chemicals \$/year
Lime feed system	483,575	192,846	4,302,000
Polymer feed system	76,472	30,496	2,965,625
Bitumen skimming	130,000	65,000	
Recarbonation system	3,355,000	100,500	1,300,000
Recarbonation settling pond	266,800	250,125	
Surge pond	917,125		
Low lift pump	216,775	121,727	
Pressure gravel filter	3,668,000	315,490	
Backwash pump	108,387	11,672	
Low lift pump	216,775	121,727	
Gravity sand filter	1,667,500	120,060	
Backwash pump	166,750	20,010	
Filter(s) backwash resevoir	45,022		
Pressure carbon columns	5,252,625	63,365	
process pump	216,775	121,727	
backwash resevoir	28,347		
backwash pump	150,075	49,171	
resevoir fill pump	58,362	22,061	
Initial carbon charge	2,000,000		
Carbon regeneration	27,500,000	4,830,000	5,110,000
TOTAL	46,644,425	6,461,573	13,677,625

Reference

U.S. EPA (1979), Estimating Water Treatment Costs.

EPA - 600/2-79-162b, Cincinnati, OH, 45268.

Appendix "B"

"Dry" Tailings Disposal from Oil Sands Mining Geotechnical Characteristics and Disposal Design

Submitted To:

C-H SYN FUELS LTD.

Submitted By:

TERRACON GEOTECHNIQUE LTD.

Submitted:

August, 1984

Principal Authors:

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Contract No:

52SS KE 145-2-0439

**PHYSICAL PROPERTIES, DEPOSITIONAL
CHARACTERISTICS AND CONCEPTUAL
DISPOSAL DESIGNS FOR LIME AND POLYMER
TREATED WHOLE OIL SAND TAILINGS**

SUBMITTED TO: C-H Synfuels Ltd. for Environment Canada Ltd.

SUBMITTED BY: Terracon Geotechnique Ltd.

SUBMITTED: March, 1984

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CONTRACT NO. 52SS KE 145-2-0439

FINAL DRAFT FOR DISCUSSION PURPOSES

TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
1.1 Scope	1
1.2 Purpose	1
1.3 Technical Approach	2
2.0 DESCRIPTION AND PROPERTIES OF WHOLE OIL SANDS TAILINGS SAMPLES ON AN "AS RECEIVED" OR BULK BASIS	3
2.1 Source and Amount of Sample	3
2.2 Processing the Whole Oil Sands Tailings Samples	3
2.3 Bulk Properties of Untreated Whole Oil Sands Tailings Samples	3
2.4 Properties of Untreated Oil Sands Tailings	4
3.0 OPTIMIZATION OF LIME AND POLYMER RECIPES	5
4.0 FLUME TANK TESTS	6
4.1 Sample Selection and Preparation	6
4.2 Equipment Specifications	6
4.3 Mixing, Aeration and Depositional Procedures	7
4.4 Summary of Experimental Results	8
5.0 PROPERTIES OF LIMED AND POLYMER TREATED WHOLE OIL SAND TAILINGS	9
5.1 Sampling Procedures	9
5.2 Index (Liquid Limit) Properties	10
5.3 Grain Size Data	10
5.4 Permeability Test Data	12
5.4.1 Vertical Permeabilities	12
5.4.2 Horizontal Permeabilities	13
5.5 Column Drainage Tests	13
5.5.1 Results of the Tests	14
5.6 Consolidation and Density Data	15
5.6.1 Consolidation Tests	15
5.6.2 Density as a Function of Depth	16
5.7 Shear Strength Data	17
5.8 Unconfined Compression Test Data	17
5.9 Particulate Content of Run-Off Water	18
6.0 LIQUEFACTION POTENTIAL ANALYSIS	19
6.1 Definition of Liquefaction	19
6.2 Steady-State Densities	19
6.3 Design Specifications to Preclude Liquefaction	21

LIST OF TABLES (Appendix A)

TABLE 1	Summary of Feedstock for Flume Tests
TABLE 2	Summary of Flume Tank Measurements and Test Samples
TABLE 3	Summary of Liquid Limit Tests
TABLE 4	Summary of Permeability Tests
TABLE 5	Summary of Unconfined Compression Tests
TABLE 6	Summary of Consolidated Undrained Triaxial Tests ($\bar{R}$)
TABLE 7	Summary of Sieve Analyses and Selected Physical Properties

LIST OF FIGURES (Appendix B)

FIGURE 1	Mixing Tank and Depositional Flume Tank Equipment Layout
FIGURE 2	Grain Size Distribution Curve for Untreated Whole Oil Sands Tailings (General Curves from Literature)
FIGURES 3 and 4	Grain Size Distribution Curves for Whole Oil Sands Tailings Treated with 1500 ppm Lime
FIGURE 5	Grain Size Distribution Curves for Lime and Polymer Treated Whole Oil Sands Tailings
FIGURE 6	Grain Size Distribution Curves for Untreated Whole Oil Sands Tailings for Selected Samples
FIGURE 7	Three Metre Vertical Drainage Column Arrangement with Pore Pressure Drainage Data
FIGURE 8	Consolidation Curves for Lime and Polymer Treated Whole Oil Sands Tailings
FIGURE 9	Predicted Dry Density as a Function of Depth for Treated Whole Oil Sands Tailings
FIGURE 10	Predicted Effective Minor Principal Stress as a Function of Depth for Treated Whole Oil Sands Tailings
FIGURE 11	Effective Shear Strength Parameters for Lime Treated Whole Oil Sands Tailings at Maximum Principal Stress Ratio (σ'_1/σ'_3)
FIGURE 12	Effective Shear Strength Parameters for Lime Treated Whole Oil Sands Tailings at Maximum Principal Stress Difference $\frac{1}{2}(\sigma'_1 - \sigma'_3)$
FIGURE 13	Effective Shear Strength Parameters for Lime and Polymer Treated Whole Oil Sands Tailings at Maximum Principal Stress Ratio (σ'_1/σ'_3 Max.)
FIGURE 14	Effective Shear Strength Parameters for Lime and Polymer Treated Whole Oil Sands Tailings at Maximum Principal Stress Difference $\frac{1}{2}(\sigma'_1 - \sigma'_3)$
FIGURES 15 to 34	Effective Confining Stress Behaviour as a Function of Axial Strain for Lime and Polymer Addition for a Range of Initial Void Ratios from 0.49 to 0.94 (inclusive)
FIGURE 35	Steady-State Points from $\bar{R}$ Tests on Consolidated Lime Treated Oil Sands Tailings

1.0 INTRODUCTION

This report describes selected laboratory and conceptual design studies to enhance the disposal and reclamation characteristics of whole oil sands tailings. The concept involves the utilization of lime and polymer addition to whole oil sands tailings and the design of disposal layouts which take advantage of treated tailings properties.

1.1 Scope

The scope of work conducted by Terracon Geotechnique Ltd. (formerly CGEI) includes a review of selected physical properties of oil sands tailings (untreated or raw) and the conduct of bench scale laboratory tests on whole oil sands tailings which have been treated with appropriate levels of lime (CaO) and/or polymer, (Canadian Cyanamide A110). The selected critical physical properties include those which affect the storage volumes (densities and void ratios), drainage characteristics, slope angles, liquefaction parameters and the particulate content of the water phase (run-off).

Application of these data to the design of conceptual disposal sites which take full advantage of the unique properties of limed and polymer treated whole oil sands tailings, encompasses the applied portion of this study.

The work has been done in conjunction with C-H Synfuels Ltd. of Calgary and Zenon Environmental Inc. of Burlington, Ontario.

1.2 Purpose

The program of study has been organized to achieve very selected technical objectives. These are stated as follows:

- o To devise and execute lime and polymer mixing techniques together with flume experiments which would assess the depositional characteristics of the whole oil sands and the potential particulate content of run-off water,
- o To measure certain physical properties of lime and polymer treated whole oil sands with special reference to flume tank deposition,

TABLE OF CONTENTS (CONT'D)

	Page
7.0 CONCEPTUAL TAILINGS POND LAYOUTS	23
7.1 Purpose	23
7.2 Design Parameters for Tailings Disposal Layouts	24
7.3 Single Stack Design with Spigotted Beaches and Filter Drains	24
7.3.1 Stack Operation	25
7.3.2 Dyke Shell Design	25
7.3.3 Run-Off Water Recycling	26
7.4 Double Stack Design with Recycle Pond	26
7.4.1 Tailings Ramps	26
7.4.2 Recycle Pond Operation	27
7.5 Alternate Disposal Configurations	27
8.0 CONCLUSIONS	27
9.0 RECOMMENDATIONS	28
APPENDIX A LIST OF TABLES	
APPENDIX B LIST OF FIGURES	
APPENDIX C PLATES 1 AND 2	

Lastly, a series of conceptual designs was undertaken to demonstrate the physical layouts of out-of-pit permanent disposal areas for oil sands tailings. These disposal schemes would be free of permanently impounded water and sludge and would provide surfaces easily amenable to reclamation activities.

2.0 DESCRIPTION AND PROPERTIES OF WHOLE OIL SANDS TAILINGS SAMPLES ON AN "AS RECEIVED" OR BULK BASIS

2.1 Source and Amount of Sample

Twenty-five, twenty-two litre pail samples of whole oil sand samples were collected on three occasions at the extraction plant operated by Syncrude Canada Ltd. The sample pails were allowed to stand for approximately one week in order to settle the solids and allow the free bitumen to separate from the other phases.

2.2 Processing the Whole Oil Sands Tailings Samples

The pails were measured to obtain the total volume, weight and volumes of water and settled solids. Percent solids for each pail were compared as a check on the representativity of the tailings in terms of the ratio of water and solids volumes. Before utilizing any of the sample materials, the floating bitumen was removed from the water surface of each sample container. Subsequently, the weights and volumes of the remainder of each sample were remeasured.

2.3 Bulk Properties of Untreated Whole Oil Sand Tailings Samples

These bulk data from whole oil sands tailings have been recorded on Table 1 in Appendix A. These data show that there is a range in the "typical" tailings percentage solids from 42.35% to 66.63% solids by weight. The other parameter which was measured and recorded included the ratio of the volume of free liquid to the volume of bulk solids, (V_l/V_s). As shown on Table 1, the bulk density for the whole tailings mass ranges from 1.36 to 1.79 while the ratio of the volume of free liquid to bulk solid volume after settlement ranges from 0.57 to 2.07.

- FIGURE 36 Standard Proctor Compaction Test of Lime Treated Whole Oil Sands Tailings
- FIGURE 37 Whole Oil Sands Tailings Conceptual Disposal Design - Single Stack with Spigotted Beaches and Filter Drains
- FIGURE 38 Whole Oil Sands Tailings Conceptual Disposal Design - Double Stack with Recycle Pond

PLATES
(Appendix C)

PLATE 1

Photograph 1 Close-up View of Flume Tank Looking Vertically Down at Sampling with Consolidation Ring (Lime Treated Tailings)

Photograph 2 Oblique View of Flume Tank (Lime Treated Tailings)

PLATE 2

Photograph 1 Flume Tank with Untreated Oil Sand Tailings

Photograph 2 Flume Tank with Treated Whole Oil Sand Tailings

iii) Sludge: generally a solid-water suspension sometimes also referred to as "slimes" or "fines" found in the central area of the discharge ponds. This suspension typically reaches equilibrium at 30 to 40% solids by volume.

Fines content (-325 m or -44 micron),	90 - 100%
Clay content (-2 micron),	≈ 50%
Grain Size Distribution,	See Appendix B, Figure 2, Curve 24
Bulk Density (γ_t),	960 kg/m ³ to 1300 kg/m ³
Effective Shear Strength (σ'),	Nil

3.0 OPTIMIZATION OF LIME AND POLYMER RECIPES

The optimum levels of lime and lime plus polymer in combination were established by Zenon on the basis of two parameters as suggested by Terracon. The first parameter which had to be optimized was the percentage of fines escaping with the run-off water. A maximum acceptable level of 1% solids by weight was set. The second controlling parameter was the drainage characteristic. Vertical permeability was chosen as the controlling drainage characteristic.

Consequently, the minimum levels of lime and lime plus polymer in combination were tentatively identified as 1500 ppm lime added as the only flocculant and at concentrations of 900 ppm when added with a polymer at concentrations of 8 mg/l. These recipe values may mean that other physical parameters such as density, void ratio and consolidation characteristics have not necessarily been optimized in terms of ultimate disposal of the tailings material. Further test work may be necessary to optimize the treatment recipes with respect to these other parameters.

- o To estimate and discuss the liquefaction potential and those densities which are required to preclude the occurrence of liquefaction,
- o To originate tailings disposal layouts for the permanent disposition of whole oil sands tailings which would be suitable for permanent reclamation.

The commercial objectives are stated as follows:

- o To devise a cost efficient method for disposing of all phases of oil sand tailings which is no more expensive than current methods, and
- o To provide a drained tailings which is reclaimable at equal or less than projected costs for current operations.

1.3 Technical Approach

A bench scale experimental approach to defining the properties and behaviour of the lime and polymer treated whole oil sands has been adopted. This approach recognizes the current field conditions and tailings disposal schemes which are now operating. The testing program has balanced the optimization of the permeability (drainage) characteristics and the entrapment of fines in the tailings sediment to minimize the particulate content in the run-off water. Optimization refers to the minimum content of lime and/or polymer which is required to reduce the fines content to less than 1% (by weight) and to provide maximum possible vertical and horizontal permeabilities. Such permeabilities would enhance the drainage characteristics, render whole oil sand tailings slopes more stable, decrease the liquefaction potential and make the tailings more amenable to reclamation on a permanent non-maintenance basis.

Determination of these optimum flocculant levels by others was followed by experiments to investigate the depositional density, void ratio, liquefaction potential and consolidation characteristics of the whole oil sands treated at optimum levels of lime and/or polymer.

4.3 Mixing, Aeration and Depositional Procedures

Whole oil sands tailings were placed in the mixing chamber, the mixer turned on and the lime and/or polymer treatments added. The flocculants were added in fluid form (CaO slurry) by injecting these chemicals below the surface of the tailings while the whole oil sand tailings were being agitated. Normally the material was mixed for 10 to 15 minutes. Occasionally the mixing time was extended to 30 minutes. The primary criterion of the mixing stage was to attain a uniform mixture with a constant consistency (viscosity) especially in the vertical direction. At this stage of the treatment, the tailings had a "thickened, coagulated" or "pudding" appearance with an apparent consistency or viscosity greater than the untreated tailings.

Mixing rotation speeds of 400 to 500 rpm were found to be sufficient with the chamber-paddle arrangement shown in Figure 1, Appendix B. Sufficient mixing refers to the minimum rotational velocity which was required to deliver a uniform batch of treated tailings without splashing or unnecessary aeration.

For flume tank tests 1 and 2 (Table 2, Appendix A), a variable speed mixer operating in the 400 to 500 rpm range was used to prepare the tailings mixtures. For the remaining flume tank tests (3 to 12, see Table 2), a high speed mixer operating at approximately 1700 rpm was utilized. As can be seen by the density values presented for these flume tests, there does not appear to be a significant difference in these density values which could be attributed to different mixing and aeration procedures. Nevertheless, it is still considered prudent to design any subsequent pilot mixing system to reduce aeration to the minimum to ensure that slurry and subsequent deposited layers of tailings have minimal entrapped gas.

Subsequently, the whole treated tailings mixture was piped to the flume tank and discharged vertically into the closed end of the flume. Discharge rates were varied. Commonly, rates of 1.5 to 2 litres per minute were used to discharge the tailings into the tank. At faster rates than these, the tank failed to retain the tailings and coarse material (sand) was washed into the run-off collector.

The average values on Table 1 provide a reasonable representation of typical tailings material. The range of values may, however, represent very short term fluctuations in the tailings lines which may not be representative of conditions at discharge points in a disposal area when large flows are being discharged.

2.4 Properties of Untreated Oil Sands Tailings

Generally, oil sand tailings will be deposited in disposal ponds in such a manner that three inter-related but distinct solid phases are generated. Each phase has a set of unique properties. In essence, these phases and their properties are typically:

- i) Dyke Sand: captured by the cell construction technique; the material is utilized to construct the retention pond dykes;

Fines content (-325 m),	3 to 4%
Grain Size Distribution,	See Appendix B, Figure 2, Curves 20 and 21
Dry Density, (γ_d)	1570 kg/m ³
Effective Shear Strength (σ'),	30°

- ii) Beach Sand: deposited during the overboarding procedure as the tailings are rapidly discharged into the pond. Generally contain a mixture of sand and fines in varying proportions but normally with the fines content increasing downslope.

Fines content (-325 m),	5 to 15%
Grain Size Distribution,	See Appendix B, Figure 2, Curves 22 and 23
Dry Density, (γ_d),	1600 kg/m ³
Effective Shear Strength (σ'),	25° to 30°

The above summary table clearly shows that the liming procedure effectively controls the fines and results in a very clean run-off water by trapping or coagulating the fines with the sand. Slope angles were greatest with untreated tailings. These relatively high slope angles in the untreated tailings are caused by a lack of fines in the tailings sand.

Polymer addition does appear to enhance slope angles.

In terms of fresh wet densities as deposited in the flume tank, the lime recipe provided the highest densities. This, of course, is a reflection of the fines entrapment. On the other hand, polymer addition does not appear to enhance fines entrapment beyond the performance of lime used alone.

5.0 PROPERTIES OF LIMED AND POLYMER TREATED WHOLE OIL SAND TAILINGS

5.1 Sampling Procedures

Small "grab" samples were selected randomly in most cases from the various layers in the flume tank experiments. Occasionally specific samples were taken from fines layers when they occurred. Usually the samples were disturbed or remoulded. Several attempts were made to obtain undisturbed samples using a specially built piston sampler with a diameter of approximately 5 cm but the lack of cohesion in the tailings materials rendered these samples inappropriate for subsequent testing.

For the purposes of consolidation tests, relatively undisturbed samples were collected directly from the flume tanks by pressing the consolidation sample holder (a ring-like device) into the sediment after allowing approximately 24 hours for drainage to take place. Subsequently, the samples were cut away and trimmed (see Plate 1, Photograph 2, Appendix C).

4.0 FLUME TANK TESTS

4.1 Sample Selection and Preparation

The 22 litre pail samples, after description and measurement as described in Section 2.2, were selected to provide a full range of solids to water ratios. Normally, an entire 22 litre pail sample was utilized for batch testing purposes. In those cases where the pail sample was sub-divided (sub-sampling), the supernatant fluid was poured off, the solids vertically sub-divided to ensure equal portions of fines in each sub-sample and then recombined with the appropriate volume of fluid to maintain the original solids to water ratio. The sub-sample was then placed in the mixer as one batch.

4.2 Equipment Specifications

Figure # 1, (Appendix B), shows the design and layout of the mixing chamber mixer, flume tank and run-off collector. Equipment dimensions are also presented in Figure 1. The tank was designed with a conical base and vertical baffles to enhance the turbulence, minimize aeration, eliminate "dead zones" and generally allow the tailings mixture to achieve a uniform density from top to bottom in a short period of time.

The original mixer was fixed at 1700 rpm approximately; later in the tests, a variable speed mixer was used with a range of 0 to 650 rpm.

The flume tank was constructed of plexiglass in order to facilitate visibility of the depositional and run-off processes. A 2 cm thick base layer of commercial 14-20 frac sand was used to line the base of the flume tank in order to simulate local ground conditions. In all tests, the flume tank was maintained in a horizontal attitude.

The run-off fluid phase was collected at the end of the flume tank to measure the particulate content of the run-off water and to obtain an approximate check on the water ratio, (retained water vs run-off water).

Note that the fines contents (-325 mesh) typically ranges between 0% and 17% with 10 to 12% probably being fairly typical of most whole oil sand tailings. Curve 22 shows the typical overboarded phase or dyke sand which is somewhat coarser than the unsorted whole oil sands tailings. Curve 23 illustrates typical beach sand phase which tends to represent the finer sand sizes of the tailings. Finally, Curve 24 is typical of the material which is found inside the tailings pond and is commonly referred to as the sludge phase. Note that this material is composed primarily of silt and clay (50% of each) sized fractions. These are the typical characteristics of fines material now being collected and stored in the large tailings ponds.

In contrast to these "background" curves of untreated tailings and their constituent phases, Figures 3 and 4 report on the distribution of particle sizes for lime treated tailings. A careful comparison and study of the curves on Figures 2, 3 and 4 is fully warranted. Flocculation has produced an average value of between 3% and 7% -325 mesh material. This is in contrast to the previously discussed values for untreated tailings of 0 to 17% with perhaps the typical values ranging between 12 and 15%. The two populations are obviously very different and this difference reflects the agglomeration and flocculation which has taken place as a result of the addition of lime. However, when other properties such as dry density and fines in the run-off water are compared with the fines contents shown for Curves 1 through 5 of Figures 3 and 4 there is no direct correlation that can be made, (see Table 7 in Appendix A).

The lime and polymer treated tailings grain size distribution curves are displayed on Figure 5. There is virtually no difference in these distribution curves and the ones which represent treatment by lime alone. The last set of Curves, 8 and 9 as shown in Figure 6, represent untreated tailings. It is noteworthy that one sample (#8) had a very high fines content (26%) which is not typical of the tailings. This material was not used in any other tests in this study. The other sample falls within the typical tailings range.

In certain tests, only one depositional layer was placed. In other cases, several layers at various time intervals were deposited. The lime/polymer recipes and combinations of recipes are reported on Table 2. Profiles of the resultant layers of whole oil sand tailings are also illustrated on this Table. Plate 1 in Appendix C provides photographs of typical lime treated whole tailings.

4.4 Summary of Experimental Results

The results of all twelve of the depositional tests are described in detail in Table 2 (Appendix A). Two series of tests were included in the study. The first series used a 900 ppm lime concentration together with 8 mg/l of polymer. The second series utilized lime only at a concentration of 1500 ppm. Table 2 also shows the flumes from which disturbed and undisturbed samples were selected for various types of physical tests. Those types of tests which were conducted are defined on the Table and discussed in subsequent sections of the report.

The critical parameters measured in the flume tank with respect to the depositional characteristics of treated whole oil sand tailings include slope angle, density and percentage of solids in the run-off water.

SUMMARY OF FLUME TANK TESTS

MATERIAL	AVERAGE WET DENSITY gm/cc	AVERAGE SLOPE ANGLE degrees	AVERAGE PERCENT SOLIDS IN RUN-OFF %
Whole Tailings with 900 ppm Lime and 8 mg/l Polymer (7 tests)	1.57	2.6	0.53
Whole Tailings with 1500 ppm Lime (12 tests)	1.69	1.2	0.39
Untreated Whole Tailings (1 test)	--	3.72	6.88

However, visual inspection of the permeameter cells during these tests failed to identify any particle movements after the settling stage had been completed.

5.4.2 Horizontal Permeabilities

Horizontal permeabilities were conducted in a small flume tank equipped with piezometer tips and a coarse sand (14-20 frac sand) berm placed across the downstream end of the tank. Flow nets were constructed on the tank based on pressure data from the piezometer tips. Horizontal permeabilities were calculated from the flow net and measured flow volumes.

5.5 Column Drainage Tests

A three metre vertical column measuring 9 cm in diameter was constructed of plexiglass tubing with a facility for drainage through the base. Stand pipe design piezometers were installed every 30 cm down the column. These were open tubes with a plastic foam type filter extending horizontally about 2 cm inside the column, (see Figure 7, Appendix B).

A sand filter, 3 cm thick, was placed at the base of the column to prevent the loss of fines from the column so as to effectively model the subsequent consolidation and drainage of the tailings slurry.

The primary objectives of the column tests were to describe the degree of homogeneity/layering of the slurry as settlement and/or consolidation took place; to measure the pore pressures as a function of time and depth and to evaluate the vertical drainage characteristics in terms of time requirements and moisture conditions.

The freshly mixed limed oil sands tailings slurry was poured into the column until the column was nearly completely filled. Thereupon, observations were made of the behaviour of the slurry until equilibrium conditions were achieved. Generally the equilibrium stage of settlement

The permeability tests were conducted on samples which were transferred as a slurry directly from the mixing tank into the vertical permeameter. The tailings were allowed to settle in the permeameter and when equilibrium had been established, generally within 24 hours, the permeability test was conducted.

5.2 Index (Liquid Limit) Properties

Samples for liquid limit index tests were collected from all flume tank tests except flume tank number 10 (see Table 2). The liquid limit test has been adopted as a simple cost efficient method to compare the uniformity of the materials deposited in the flume tanks.

The results of the Liquid Limit tests are presented in Table 3. The values are extremely low with a narrow range extending from 11.4 to 13.7. The narrow range tends to indicate that the materials in the flume tank tests are generally quite similar in terms of their grain size distribution curves and fines contents. That is, the materials are uniform and probably isotropic. The low values indicate a relatively low fines content (minus 325 mesh).

Two tests provided results of 44.4 and 58.0. These results are typical of high fines materials and represent clay layers which developed in two of the flume tanks. These layers resulted from improper mixing of the flocculants and perhaps from dyking. In both cases in which a separate fines layer developed lime and polymer had been added to the tailings rather than lime alone.

5.3 Grain Size Data

Figure 2 illustrates the typical grain size distribution curves of untreated whole tailings as well as its commonly found phases in the currently operating ponds. In particular, curves 20 and 21 provide an envelope which represents the range of grain sizes for whole oil sand tailings.

Drainage in the first 15 hours was most pronounced, as shown on the vertical pore pressure profile in Figure 7, Appendix B. Thereafter, drainage became progressively slower and after 159 hours, i.e. one week approximately, the three metre column of sediment had reached drainage equilibrium. In effect, whole tailings sand layers 3 metres in thickness with only vertical drainage (no lateral drainage) and no additional surface recharge would be effectively drained in approximately one week.

The average moisture content after one month's drainage in the column was 29.3%.

5.6 Consolidation and Density Data

5.6.1 Consolidation Tests

Six samples of treated whole oil sands tailings were selected for consolidation testing. Results are presented in Figure 8, Appendix B. In all of the tests the samples were initially loaded to approximately 0.25 tsf (23.9 kn/m^2) and allowed to consolidate; then unloaded to a value of 0.01 tsf (9.58 kn/m^2); finally, the samples were consolidated in geometric progression to 16 tsf (1532.8 kn/m^2). Curves 1, 2 and 3 in Figure 8, Appendix B show the consolidation characteristics for the lime treated (1500 ppm) whole tailings. Curves 1 and 2 represent remolded material and are very similar in shape i.e. show very similar consolidation characteristics. Void ratios in the range of 0.75 to 0.6 appear to be typical for this material. Curve 3 illustrates the consolidation characteristics for undisturbed whole tailings treated with 1500 ppm of lime. This material is much more sensitive (void ratio range of 1.5 to .8), to loading than is the remolded material. This would suggest that the limed floc structure of the fines is sensitive to reworking and undergoes collapse to some degree when the material is reworked.

The recipe which includes lime and polymer results in a material which is less sensitive than the lime only recipe. More importantly, one of the tests (Number 6) provided an initial void ratio of approximately 0.56 and a final void ratio of 0.54.

5.4 Permeability Test Data

5.4.1 Vertical Permeabilities

These values are provided in Table 4. Most values are in the 1×10^{-5} to 10×10^{-5} cm/sec range which is indicative of moderate drainage characteristics. The lime/polymer recipe provided an average K_v of 6.87×10^{-5} cm/sec. For the lime only recipe, an average value for K_v of 5.20×10^{-5} cm/sec. was obtained. The difference between these values is not significant. Note also that there is a very good agreement between the vertical and horizontal permeability values. This provides an additional indication that the material is reasonably isotropic and is being deposited as a homogeneous medium, rather than a layered one.

In all cases, the vertical permeability experiments were conducted in a cylindrical permeameter measuring 25 cm high and 7.5 cm in diameter. The tests were conducted over a 24 hour period and the treated tailings were placed in the permeameter as a slurry or in a partially drained, semi-solid or "plastic" state. Permeability results do not appear to be sensitive to the method of placement of the material in the permeameter cell. Once again, this is an indication that the material is reasonably isotropic.

Permeability values were measured at various time increments over the period of the tests. In all cases, in which lime and lime/polymer were added to the tailings, several hours were required for the permeability values to stabilize and become repeatable. In all cases, the reported permeability values are those reached at equilibrium. In all cases, permeability values decreased with time until equilibrium or repeatable values were obtained. The greatest changes in permeability values occurred within the first 60 minutes of the permeability test. Thereafter, changes were much slower until no changes were recorded after 24 hours of monitoring. The time required to reach equilibrium is probably a result of soil structure changes which take place within the whole oil sands tailings as a result of the movement of the fines or fines flocs.

5.7 Shear Strength Data

Figures 11 to 14 (Appendix B) inclusive present the results of triaxial undrained shear strength tests for both lime and lime and polymer treated whole oil sand tailings. The angle of internal friction (effective shear strength) for lime and polymer treated whole oil sand tailings has been determined to be 37.6° to 34.5° . The effective cohesion (c') is zero. The laboratory results are based on consolidated undrained triaxial ($\bar{R}$) tests with pore pressure measurements as shown in Figures 15 to 34.

For lime only treated whole oil sands tailings, the corresponding ϕ' value ranges from 31.0° to 34.5° , while the effective cohesion c' is zero. These data indicate that the lime and polymer recipe provides a material which has distinctly higher shear strength parameters as opposed to the lime only treated tailings.

5.8 Unconfined Compression Test Data

Unconfined compression data have been collected in order to measure the relative differences in the shear strength characteristics of treated oil sand tailings (see Table 5, Appendix A). The data have also been used to obtain an approximate measure of the effects of "curing" treated tailings as a function of time. The tests were run at very low strain rates to ensure that pore pressure build up did not take place.

Tests on the fresh samples treated with both lime and polymer provided average peak strength values of 14.05 and 13.21 kPa with corresponding dry density of 1.76 and 1.74 gm/cc. After 7 days and allowing the samples to air dry at room temperature the strengths had increased to 376.77 and 243.20 kPa respectively with corresponding dry densities of 1.78 and 1.69 gm/cc. Thus the strength increases with time are real. They are a result of the mineral grains undergoing some form of bonding. These increases in shear strength are not a result of increased density and are therefore not frictional but cohesive in nature. This shear strength increase as a function of time may be similar to the change in strength which takes place in cement as it cures. The polymer addition does not appear to enhance these strength increases.

was reached when the sediment-clear water interface stabilized at some minimum level. At this point readings in the piezometers were noted for the static condition i.e. all equal heads above some reference datum. At this time, drainage of the tailings slurry was commenced through the valve at the base of the column. Thereafter, readings of the piezometers were made at daily or twice daily frequency. The readings were discontinued when piezometer readings stabilized. Samples were selected from the column for moisture content determination.

5.5.1 Results of the Tests

Two drainage tests were conducted. The first test used a tailings slurry with approximately 50% solids and an addition of 1500 ppm of lime. As with all tests, ambient room temperatures of 18 to 20°C were maintained. The slurry was gently and continuously poured into the column until the column was nearly full, (20 cm below top of column). Piezometer standpipes were filled with water previously to the same level as in the column. Piezometer valves were opened to allow each tip to reach equilibrium with fluid pressures in the column.

As in the case of the 1 litre cylinder mixing and settling tests, the slurry develops the classic "curdled" appearance and a clear supernatant liquid appears within a few minutes. In addition, 25 to 30 cm of foam accumulates on the top of the supernatant liquid.

During the settling process, macroscopically, the slurry appears quite uniform from the top to the bottom of the column. Microscopically, the settlement process manifests itself in vertical streams or trails of separated clear water moving "up" the column relative to the solids which are moving "down" the column. Air bubbles incorporated during the mixing process rise in and with the fluid streams.

6.0 LIQUEFACTION POTENTIAL ANALYSIS

6.1 Definition of Liquefaction

Loose, saturated sands, particularly fine sands, are unstable, in the sense that application of shear stresses causes the structure of such sands to tend to decrease in volume, i.e., to contract. If no drainage is allowed during shear, large pore water pressures build up and the shear resistance of the sand decreases. If the sand is loose enough, the structure collapses during shear and the loss in strength after the peak strength has been reached is sudden and pronounced. At this moment, the material behaves more as a fluid than as a solid. This loss in strength is referred to as liquefaction. The shear strength that remains after liquefaction is referred to as the steady-state shear strength.

Evaluation of liquefaction potential requires knowledge of that density (which varies with soil type (grain size) and effective confining stress) at which a saturated mass of sand will not lose strength during undrained shear. More specifically, a soil is liquefiable if the density is equal to or less than the steady-state density at the in-situ level of confining effective stress. In other words, liquefaction will not occur unless the static shear stress at that depth actually exceeds the steady-state strength at that depth.

6.2 Steady-State Densities

In order to evaluate the steady-state densities as a function of effective confining stresses versus the method of treatment of the tailings, a series of undrained triaxial tests ($\bar{R}$ tests) were completed. The tests were completed on carefully prepared samples of lime and lime and polymer treated whole oil sands tailings over a void ratio or density range appropriate to the values which were obtained from the flume tank experiments (see Table 2) and therefore might be anticipated in a disposal stacking scheme. This void ratio range extends from 0.51 to 1.23 which is equivalent to a dry density range extending from 1.76 to 1.19 gm/cc (see Table 2). A single dry density of 1.95 gm/cc, measured in flume tank 9, may be spurious and hence has been disregarded.

These values are close to those which are typical of high grade oil sand in the in-situ state. Based on these test results, remolding of polymer treated material increases the void ratio. This behaviour is in direct contrast to the lime treated material.

More importantly, the data, as shown in Figure 8, should be refined to determine optimum ratios of lime and polymer as well as total amounts in order to provide the best possible (i.e. lowest) void ratios and maximum densities. Furthermore, one other variable has been introduced. Curve 6 is based on a sample taken from a dyked flume tank. Sample 1 was taken from an open ended flume tank. The full effect of this parameter (dyking) should be investigated further.

It is tentatively concluded that under certain conditions it is possible for the deposited whole oil sands, after treatment with either lime at 1500 ppm or lime at 900 ppm and polymer at 8 mg/l, to achieve void ratios which are similar to the higher end of the void ratio range of some in-situ oil sands (see Curve 6, Figure 8, Appendix A). This property or behaviour is an extremely important finding in terms of its impact on both volume/area requirements for tailings disposal designs and liquefaction potential. This treatment has the potential to provide a material with volume requirements which could be significantly lower than untreated oil sands tailings.

5.6.2 Density as a Function of Depth

Figure 9 (Appendix B) shows the effect of burial of the lime and or lime/polymer treated whole oil sands. The density ranges for depths up to 160 metres have been computed for lime and lime and polymer treated material. For lime treated material dry densities ranging from 1500 kg/m^3 to 1570 kg/m^3 appear to be reasonable. For lime and polymer treated material they vary from 1450 to 1580 kg/m^3 . However, values up to 1670 kg/m^3 have been attained. Further test work to determine the sensitivity of this parameter to the recipe values may be warranted.

Generally, as shown on Figures 15 to 34, the " $\bar{B}$ " values after consolidation ranged from 0.5 to 0.97. These low " $\bar{B}$ " values may be caused by the generation of a gas within the sample. This problem was experienced in both Terracon's and Thurber's laboratories where the $\bar{R}$ tests were conducted.

2. The $\bar{R}$ test data indicate that some of the samples may have been remolded to densities which are greater than the steady-state density for the given level of consolidation and initial confining stress. However, this is the inevitable result of a trial and error approach which is the only method available. Additional testing in the lower density range, specifically void ratios from 0.75 to 0.95, must be done.
3. The consolidation stage was conducted for an all-round pressure range for lime treated samples from 25 to 300 kPa. For the lime and polymer treated samples the all-round consolidation pressure ranged from 50 to 475 kPa. In all cases isotropic consolidation (i.e. $\sigma'_1 = \sigma'_3$ or $K_c = \sigma'_1/\sigma'_3 = 1.0$) was conducted. Because geostatic stress conditions are not always isotropic some further test work needs to be done with all-round consolidation ratios (K_c) equal to 2.0.

6.3 Design Specifications to Preclude Liquefaction

The void ratio data and dry density data reported for the $\bar{R}$ tests on Figure 35 may be used as a guide to indicate the densities which are required to preclude isotropic liquefaction on any given confining effective stress. The lower boundary of the steady-state envelope in the figure identifies the minimum required densities/void ratios which the whole oil sands tailings must attain in the in-situ condition.

The results of the two week cure tests are ambiguous in the sense that the strength of the lime treated tailings decreased relative to the 1 week curing time. On the other hand, the lime and polymer treated specimens continued to show strength increases (243.2 to 314.22 kPa). Density values for all series of tests remain relatively constant.

It can be concluded that the air drying of the lime and lime plus polymer treated tails does contribute to the shear strength of the tailings. Furthermore, the shear strength increase is probably bonding or cohesive in nature rather than frictional.

5.9 Particulate Content of Run-Off Water

Reference to Table 2 (Appendix A) shows the results of the particulate (solids) content of the run-off water. Table 7, (Appendix A), also presents a listing of the solids content of the run-off water together with other physical property test data pertaining to the same flume tank tests. The data clearly show that the run-off water has a particulate content at 0.39% for lime treated tailings and slightly over 0.5% for lime and polymer treated tailings. Untreated whole oil sands produced a comparable level of nearly 7% under identical flume tank test conditions. The generally low level of solids concentration did not allow an analysis of the particulate material to be made but it is anticipated that the particulate content is all less than 2 microns in diameter and would be composed of clay mineral species rather than quartz.

The run-off water has a sufficiently low enough particulate content that would allow it to be recycled numerous times. Subsequent treatment and testing of this recycled run-off is discussed in the recommendations of this report.

7.0 CONCEPTUAL TAILINGS POND LAYOUTS

7.1 Purpose

This chapter of the report applies in a very preliminary manner, the laboratory data generated herein to the design of disposal layouts for placing drainable tailings.

Technically, current tailings ponds have two major problems associated with their design. These are:

1. Accumulation of fines or sludge (primarily -325 mesh size quartz and clay minerals) in large containment areas or "ponds", which will not separate by settlement and consolidation into water and solid phases which can be left in a permanent form satisfactory to reclamation standards.
2. A high percentage of water is retained in the tailings sludge. For example, a 109,000 BPD oil sand plant (Syncrude size) will produce approximately $474 \times 10^6 \text{ m}^3$ of sludge over 25 years which is comprised of 60 - 70% water by weight which is permanently impounded.

In essence, if the solid and water phases are easily or conveniently separable, then several options follow which greatly reduce tailings disposal costs. The advantages include:

- a) Reduced pond size including elimination of sludge and early return of tailings to mined out area,
- b) Reclaimable tailings product,
- c) Lower make-up water requirements, and
- d) Lower pumping costs.

As described in the previous section (6.1), the shear strength of a sand which remains after liquefaction is referred to as the steady-state strength. This strength may be measured in the $\bar{R}$ test. This test is conducted as a standard triaxial test procedure known as the consolidated undrained test.

The results of the individual tests on whole oil sands tailings samples which were treated with two lime and lime and polymer recipes as presented in Figures 15 to 27 in Appendix B. The data from these tests are summarized in Figure 36 in which the effective minor principal stress at which the materials develop constant shear strength at extended axial strains are plotted against their corresponding void ratios or densities. The lower limit of the envelope which best fits the data defines the steady-state densities for treated whole oil sands tailings for confining effective stresses ranging from 1.0 to 1000 kPa.

This stress range conforms to the stress range for depths down to 120 metres for stacked whole oil sands tailings. This relationship is also illustrated on Figure 10, Appendix B, as based on independent consolidation tests.

However, it is important to note that the data in Figures 15 to 34, Appendix B, will require some follow-up testing in order to clarify certain questions which arise with respect to the conduct of the tests. These are reiterated as follows:

1. The " $\bar{B}$ " value is defined as the ratio of the increase in pore pressure in the sample to the increase in confining stress (all pressure, i.e. $\Delta u / \Delta \sigma_3$). Normally the " $\bar{B}$ " value should be greater than 0.95 and in all of the $\bar{R}$ tests this value (0.95) or greater was attained prior to the consolidation of the samples. However, after the first stage (consolidation) of the $\bar{R}$ test had been completed it was not possible to obtain a high " $\bar{B}$ " value.

Initially, the drainage of run-off water would be handled by the pre-existing natural drainage channel. Encroachment of the tailings on this channel would be prefaced by construction of a filter sand and pipe drain to the recycle pond. A second recycle pond, if necessary, could be located at the upstream end as soon as sufficient elevation in the tailings had been established to allow drainage in the opposite direction.

7.3.1 Stack Operation

The dyke shell would be constructed as an "upstream" structure in perimeter segments on a 1 to 3 m lift basis. Spigots would be placed in perimeter segments around the stack to ensure orderly upward development of the stack. Tailings layers, not thicker than 3 m, should be given adequate time to drain before recommencing spigotting operations in any given location. It is anticipated that recycle pond operations could be commenced within a few months of beginning the operation of the extraction plant.

The original natural drainage would, of necessity, be rerouted. Filter drains would be directed to toe ditches around the outside perimeter of the stack dyke and then could be directed to the recycle pond itself. Since it is not known at this time what the rate of fines build-up (if any) in the run-off water will be, treatment procedures for this water remain to be determined.

7.3.2 Dyke Shell Design

Details of the dyke shell design are not within the scope of the present study. However, filter drains, toe ditch drains, compaction and density requirements and foundation stability criteria would have to be set out to ensure a safe, stable dyke design. It is anticipated that an upstream construction mode, with 3:1 downstream slopes, would be followed in the design. Furthermore, the tailings would be compacted in thin lifts after drainage over a suitable period of time. The proctor compaction test results (Figure 36, Appendix B) together with the column drainage test indicate that a reasonable cycle time should be sufficient to allow tailings moisture content to reach optimum levels for adequate track compaction.

These data, particularly those at the higher stress value of the envelope (2600 kPa), require further test work to confirm the required densities and to investigate the apparent relatively large range of densities at the higher stress levels. At the present time it is suggested that this may be due to gas generation in the samples during the execution of the compression portion of the $\bar{R}$ test. This results in a relatively low $\bar{B}$ value which in turn causes inaccuracies in the pore water and confining stress measurements.

The data also indicate that there is no difference between the lime treated whole tailings and the lime and polymer treated whole tailings. In addition, all tests were completed on freshly treated samples. Air drying effects or curing effects have not been tested to ascertain the effects of this phenomenon on the steady-state envelope.

Data produced by others indicates that the steady-state line for treated whole oil sands has shifted to a slightly higher density value relative to untreated tailings dyke sand. This difference is attributed to two factors;

- a) The inherent density of the treated whole tailings will be greater than untreated tailings sand because of the packing of the fines around the sand grains and,
- b) The lower permeability of the treated whole oil sand tailings relative to untreated tailings or dyke sand would tend to increase the liquefaction potential of the treated tailings because pore pressures would build faster and be retained longer under static liquefaction conditions.

The data in Figure 35 (Appendix B) when compared to the dry densities given in Table 2 (Appendix A) and the predicted dry densities and depths in Figures 9 and 10 (Appendix B), provide a strong indication that for tailings stacks 100 m or less the effective minor stress will be in the order of 900 kPa. At those depths dry densities in the order of 1.75 T/m^3 would be required to preclude liquefaction.

7.4.2 Recycle Pond Operation

It is anticipated that operation of the recycle pond could begin within 6 months to a year of beginning the extraction plant operations. Optimization of the disposal and stack operation could be enhanced by minimizing the elevation of the free water surface such that the treated tailings are able to fully drain. This would also allow maximum recovery of water and minimize the tailings pore water.

7.5 Alternate Disposal Configurations

The two optional layouts, as described in the previous section, would be modified to suit local topographic conditions and also to allow alternate disposal areas. Such alternate disposal areas would permit the tailings discharge stacks to be rotated at some frequency which in turn would allow additional time for the tailings layers to drain, consolidate and cure.

Other disposal layout variations which are suggested as warranting detailed study in the next phase of work include:

- a) Examination of the layout of treated tailings to in-pit disposal,
- b) Application of a "downstream" dyke shell design and layout, and
- c) Systematic layouts to include various other natural topographic features which may be available and would reduce dyking costs.

8.0 CONCLUSIONS

The addition of 1500 ppm lime under controlled conditions results in material which is, for practical purposes, isotropic and homogeneous. The flume tank sluicing procedure, developed in the laboratory, demonstrates that a run-off water suitable for recirculation with a particulate content equal to or less than 0.5% is achievable.

7.2 Design Parameters for Tailings Disposal Layouts

Based on the results of the bench scale testing program, the physical characteristics of limed whole oil sands and tailings treated with both polymer and lime, there does not appear to be a consistent difference in their properties which would dictate a choice of one recipe over the other. The following summary table highlights the properties of the two recipes:

<u>Property</u>	<u>Lime Treatment Only</u>	<u>Combined Lime and Polymer Treatment</u>
Fines Content in Run-Off Water	0.39%	0.53%
Dry Density Ranges	1560 - 1570 kg/m ³	1450 - 1670 kg/m ³
Permeabilities	5.20×10^{-5} cm/sec	6.87×10^{-5} cm/sec
Effective Shear Strengths	31° - 34.5°	34.5° - 37°
Degree of Homogeneity	Good	Good

However, the lime and polymer combined treatment produces a tailings product which has marginally superior properties to the lime only treated material in terms of tailings disposal requirements. For purposes of the disposal layouts it has been assumed that the tailings have been treated with the lime/polymer recipe.

7.3 Single Stack Design with Spigotted Beaches and Filter Drains

Figure 37 illustrates, in schematic plan and section format, the major components for a single stack out-of-pit tailings disposal scheme. The overall stack has been given an elliptical shape with the major axis extending across a natural broad valley. The minor ellipse axis parallels the valley drainage and locates the main drainage channel for run-off water to be returned to the recycle pond. The stack area would be enclosed by a compacted shell dyke with 3:1 slopes and internal filters. Spigots would be used to discharge and spread the limed tailings on an area or cell basis. A beach slope up to 5% would be expected. The compacted shell dyke would be constructed and compacted with caterpillar tractors in shallow lifts.

Specifically, the studies which should be undertaken include;

- o Further consolidated undrained tests to verify the steady-state strength for treated tailings,
- o Evaluate the rate of increase (if any) in the run-off fines content as a function of recycling the run-off water,
- o Design and cost estimate a field test program using a tailings line at an operating tailings disposal site,
- o Evaluate the ratio of retained water to run-off water particularly as a function of drainage times, and
- o Evaluate the cost and availability of locally produced lime using bitumen derived coke as kiln fuel and the limestone from the Waterways Formation.

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7.3.3 Run-Off Water Recycling

Test work has not yet been done to ascertain the cumulative effect on the fines content caused by recycling the run-off water. Because the fines content of the run-off water for the first cycle did not correlate with the fines content of the tailings (see Table 7, Appendix A), it is anticipated that recycling will not cause a "build up" of fines in the run-off water. Bench testing should be conducted to verify the projected fines accumulation in the tailings recycle water.

Detailed design work would be necessary to size the recycle pond. It is also anticipated that water recycling could begin within 6 months to one year of extraction plant operation.

7.4 Double Stack Design with Recycle Pond

Figure 38 displays, in plan and section, schematic views of the central discharge concept for placing treated tailings. A twinned stacking arrangement serviced by a single water recovery and recycle pond has been included as part of the design. Key components in this design would include tailings lines ramps to the centre of each stack, a dyke or shell constructed of local materials (perhaps overburden stripping from the mine site) as initial starter dykes and a recycle pond. The starter dykes would have a height of approximately 10% of the total stack heights which are envisaged to be in the order of 80 to 100 metres.

7.4.1 Tailings Ramps

These ramps would have be constructed in systematic thin lifts of tailings and compacted to minimum densities at moisture contents close to optimum to ensure adequate stability and bearing capacity. Ramp widths in the order of 75 metres are envisaged. The layout, as shown in Figure 38, could be optimized by spacing and sizing the recycle pond such that the stacks are close together as volume requirements will permit.

APPENDIX A TABLES 1 TO 7

Furthermore, moderate permeabilities allow the material to drain freely and hence stabilize reasonably quickly. In practical terms, it would appear that cells in a disposal area could be recycled on frequency measured in weeks.

The material must achieve densities ranging from approximately 1600 to 1800 kg/m³ dry unit weight in order to ensure that liquefaction of the material be precluded. Furthermore, long term drainage, consolidation and curing through undefined chemical reactions, could permit higher shear strengths and hence reduce liquefaction potential. In the flume tanks, after a day or two of drainage, the liquefaction potential did appear to be substantially reduced, and in no case did underlying drained layers show any tendency to liquefy when additional layers of tailings were added to the tank.

In terms of the possible tailings disposal area layouts several geometries and components, including multiple cells as stacks, filter drains and overflow reclaim ponds, have been examined and included in the conceptual layouts.

These conceptual layouts take advantage of the key enhanced properties of limed whole tailings including drainage, entrapment of fines, low particulate content of the run-off water and moderate shear strengths.

9.0 RECOMMENDATIONS

The results of this study warrant proceeding to the next stage of the investigation. This stage should examine the practical aspects of liming the tailings, cell or area disposal techniques and investigating run-off water characteristics and recycle times from one disposal area to another.

In conjunction with this pilot field test, additional laboratory test work should be done to confirm certain parameters.

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TABLE 1 SUMMARY OF FEEDSTOCK (In Five Gallon Pails) FOR FLUME TESTS

Sample No.	Lime/Polymer Treatment	Liquid to Solid Ratio by Volume (V_L/V_S)	Bulk Density (γ_{Bulk}) (gm/cc)	Percentage Solids (%) (Vol.)
83628	Lime - 900 ppm Polymer - 8 mg/l	1.43	1.52	50.24
83722 (10)	Lime - 1500 ppm	0.64	1.68	65.47
83722 (9)	Lime - 900 ppm Polymer - 8 mg/l	0.85	1.57	61.0
83722 (8)	Lime - 900 ppm Polymer - 8 mg/l	0.61	1.73	66.36
83722 (7)	Lime - 900 ppm Polymer - 8 mg/l	0.59	1.74	65.94
83714 (2)	Lime - 900 ppm Polymer - 8 mg/l	0.59	1.76	66.63
83718 (5)	Lime - 1500 ppm	0.67	1.71	64.67
83715 (4)	Untreated	0.62	1.74	61.9
83714 (1)	Lime - 1500 ppm	0.57	1.74	67.36
83714 (3)	Lime - 900 ppm Polymer - 8 mg/l	0.58	1.79	66.71
83610	Lime - 900 ppm Polymer - 8 mg/l	1.23	1.55	50.0
83518	Lime - 900 ppm Polymer - 8 mg/l	1.17	1.56	54.53
A910	Lime - 900 ppm Polymer - 8 mg/l	2.64	1.36	50
8363	Lime - 900 ppm Polymer - 8 mg/l	1.52	1.59	48.33
83428	Untreated	1.25	1.56	54.74
A810	Untreated	2.07	1.35	42.35
83428 A810 (1)	Lime - 1500 ppm	1.46	1.66	48.0
83428 A810 (2)	Lime - 1500 ppm	1.46	1.73	48.05
83412	Lime - 1500 ppm	1.18	1.54	55.1
83321	Lime - 1500 ppm	1.01	1.57	55.62
83325	Lime - 1500 ppm	1.20	1.54	54.93
8334	Lime - 1500 ppm	1.45	1.55	52.33
83225	Lime - 1500 ppm	1.22	1.57	52.26
83222	Lime - 1500 ppm	1.04	1.49	55.5
AVERAGE VALUES		1.12	1.61	56.35

NOTE: Physical property data represents untreated tailings.

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TABLE 3 SUMMARY OF LIQUID LIMIT TESTS

Test No.	Sample No.	Flume Tank Test	Liquid Limit (%)	Lime/Polymer Treatment	Remarks
1	83222	12	12.7	Lime - 1500 ppm	Single layer
2	83225	11	11.5	Lime - 1500 ppm	Single layer
3	83518/8363	4 & 2	11.7	Lime - 900 ppm Polymer - 8 mg/l.	Two layers
4	83610	3	11.7	Lime - 900 ppm Polymer - 8 mg/l.	Single layer
5	83428A810(2)	7	12.3	Lime - 1500 ppm	Single layer
6	83321/83225	11	11.3	Lime - 1500 ppm	Two layers
7	A910	6	13.7	Lime - 900 ppm Polymer - 8 mg/l.	Single layer
8	83428A810(2) 83412	7 & 8	11.8	Lime - 1500 ppm	Three layers
9	83610	3	44.4	Lime - 900 ppm Polymer - 8 mg/l.	Top layer of fines from up-stream area of flume tank
10	83610	3	58.0	Lime - 900 ppm Polymer - 8 mg/l.	Top layer of fines from up-stream area of flume tank
11	83715 (4)	--	10.7	Untreated	Sample from downstream end of flume tank
12	83412/83325/ 8334	8	12.1	Lime - 1500 ppm	Three layers
13	83628	2	10.6	Lime - 900 ppm Polymer - 8 mg/l.	Single layer
14	83715 (4)	--	10.5	Untreated	Sample from upstream end of flume tank
15	83628/A910/ 8363	2, 5	12.6	Lime - 900 ppm Polymer - 8 mg/l.	Four layers
16	83628	1	11.4	Lime - 900 ppm Polymer - 8 mg/l.	Single layer
17	8363	2	11.9	Lime - 900 ppm Polymer - 8 mg/l.	Single layer
18	83428 A810 (1)/(2)	7	11.9	Lime - 1500 ppm	Two layers
19	83628/A910/ 8363	2, 5	11.8	Lime - 900 ppm Polymer - 8 mg/l.	Four layers
Average L.L. 1500 ppm Lime = 11.94% Average L.L. 900 ppm Lime plus 8 mg/l of polymer = 11.93% (excluding fines) Average L.L. Untreated = 10.6%					
Note: All samples were taken from flume tank tests.					

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TABLE 5 SUMMARY OF UNCONFINED COMPRESSION TESTS

Test No.	Lime/Polymer Treatment	Moisture Content (%) (Air Dried)	Time to Dry in Air	Dry Density (γ Dry) (gm/cc)	Maximum Vertical Stress (σ_v) (kPa)
1	Lime = 1500 ppm	6.47	Fresh	1.95	26.83
2	Lime = 1500 ppm	6.67	Fresh	1.73	12.09
3	Lime = 1500 ppm	6.32	Fresh	1.56	7.23
4	Lime = 1500 ppm	6.35	Fresh	1.69	16.12
5	Lime = 1500 ppm	10.26	Fresh	1.78	10.87
6	Lime = 900 ppm Polymer = 8 mg/l.	6.71	Fresh	1.70	12.09
7	Lime = 1500 ppm	9.68	Fresh	1.89	13.29
8	Lime = 1500 ppm	9.64	Fresh	1.69	11.89
9	Lime = 1500 ppm	0.06	7 days	1.86	431.83
10	Lime = 1500 ppm	0.27	7 days	1.81	338.12
11	Lime = 1500 ppm	0.21	7 days	1.68	360.37
12	Lime = 1500 ppm	0.37	8 days	1.95	683.72
13	Lime = 900 ppm Polymer = 8 mg/l.	9.32	Fresh	1.78	14.32
14	Lime = 1500 ppm	0.32	2 weeks	1.83	202.03
15	Lime = 1500 ppm	0.41	2 weeks	1.74	299.46
16	Lime = 1500 ppm	0.53	2 weeks	1.64	164.52
17	Lime = 900 ppm Polymer = 8 mg/l.	0.35	1 week	1.72	268.23
18	Lime = 900 ppm Polymer = 8 mg/l.	0.31	1 week	1.65	218.17
19	Lime = 900 ppm Polymer = 8 mg/l.	0.56	2 weeks	1.71	276.98
20	Lime = 900 ppm Polymer = 8 mg/l.	0.20	2 weeks	1.75	351.45
Average 1500 ppm Lime fresh				1.76	14.05
Average 1500 ppm Lime 7 days				1.78	378.77
Average 1500 ppm Lime 2 weeks				1.74	222.00
Average 900 ppm Lime plus 8 mg/l. Polymer fresh				1.74	13.21
Average 900 ppm Lime plus 8 mg/l. Polymer 1 week				1.69	243.20
Average 900 ppm Lime plus 8 mg/l. Polymer 2 weeks				1.73	314.22
Note that 8 day test for lime treated material has not been included in averages.					

TERRACON GEOTECHNIQUE LTD.

TABLE 2. SUMMARY OF FLUME TANK MEASUREMENTS AND TEST SAMPLES

Flume Tank E.P.T. No.	Sample No.	Lime/Polymer Treatment	Wet Density (gm/cc)	Dry Density (gm/cc)	Moisture Content (%)	Percentage of Solids in Slurry	Slope Angle (degrees)	Laboratory Test Samples					DEPOSITIONAL PROFILE	
								L.L.	G.S.A.	T.T.	C.T.	Pm.T.		U.C.T.
1	83628	Lime - 900 ppm Polymer - 8 mg/l				50.24	1.86	X	X					
2	83628 Layer over	Lime - 900 ppm Polymer - 8 mg/l	1.57	1.40		50.24	4.72	X						
	A910 Layer Over	Lime - 900 ppm Polymer - 8 mg/l	1.57	1.40		50.0	4.0	X						
	8363	Lime - 900 ppm Polymer - 8 mg/l	1.57	1.40		49.2	1.4	X				X		
	83610	Lime - 900 ppm Polymer - 8 mg/l				50.0	3.58	X		X		X		
4	83518	Lime - 900 ppm Polymer - 8 mg/l				54.15	1.29	X	X					
5	A910	Lime - 900 ppm Polymer - 8 mg/l				50.0	1.58	X	X			X		
6	A910	Untreated				50.0	3.72	X						
7	83428 A910 (2) Layer over	Lime - 1500 ppm	1.58	1.19	(37.2)	48.0	1.05	X	X		X	X		
	83428 A910 (1)	Lime - 1500 ppm				48.0		X	X		X			
	83412 Layer over	Lime - 1500 ppm	AVG 1.47	AVG 1.28		55.1		X			X			
	83325 Layer over	Lime - 1500 ppm				54.93		X			X			
9	83428 A910 (2) Layer over	Lime - 1500 ppm	1.55		(31.6)	52.33	1.59	X			X			
	83412	Lime - 1500 ppm	AVG 1.51	AVG 1.40	7.6	48.0	0.94	X			X	X		
	83321 Layer over	Lime - 1500 ppm	2.07	1.95		55.1	0.86	X			X			
	83225	Lime - 1500 ppm	1.63	1.37	17.2	55.62	NIL	X			X			
11	83321 Layer over	Lime - 1500 ppm	AVG 1.97	AVG 1.76	24.54	55.62	1.81	X	X		X			X
	83225	Lime - 1500 ppm	AVG 1.67	AVG 1.32	26.54	52.26	0.40	X			X	X		X
	83222	Lime - 1500 ppm	AVG 1.76	AVG 1.44	22.21	54.45	1.81	X	X		X			X
								X			X			X

Notes: L.L. - Liquid Limit Test
G.S.A. - Grain Size Analysis
T.T. - Consolidated Undrained Triaxial Test
C.T. - Consolidation Test
Pm.T. - Permeability Test
U.C.T. - Unconfined Compression Test
Vertical bar in laboratory test sample columns indicates a sample of mixed batch origin.

TERRACON GEOTECHNIQUE LTD.

TABLE 7 SUMMARY OF SIEVE ANALYSIS AND SELECTED PHYSICAL PROPERTIES

Test No. (Grain Size Curve No.)	Flume Tank	Sample No.	Sample Treatment	Average Dry Density Yd (gm/cc)	Fines Content in Run-off Water (%)	-325 Mesh (%)
1	12	83222	Lime - 1500 ppm	1.76	1.81	7%
2	8	8334	Lime - 1500 ppm	1.28	0.27	3%
3	8	8334/83325/ 83412	Lime - 1500 ppm	1.28	0.27	2%
4	7	83428A810 (1) & (2)	Lime - 1500 ppm	1.19	nil	6%
5	11	83321/83225	Lime - 1500 ppm	1.54	1.07	7%
6	5	A910	900 ppm lime/ 8 mg/litre polymer	--	nil	4%
7	2	83628	900 ppm lime/ 8 mg/litre polymer	1.57	0.76	4.5%
8	--	83715 (4)	Untreated	--	--	27%
9	--	83715 (4)	Untreated	--	--	8%
10	4/2	83518/8363	900 ppm Lime/ 8 mg/litre polymer	--	0.73	3%
11	2	8363	900 ppm Lime/ 8 mg/litre polymer	1.40	1.05	2.5%

TERRACON GEOTECHNIQUE LTD.

TABLE 4 SUMMARY OF PERMEABILITY TESTS

Test No.	Lime/Polymer Treatment	Coefficient of Vertical (Kv) or Horizontal (Kh) Permeability (cm/sec) x 10 ⁻⁵
1	Lime - 900 ppm Polymer - 8 mg/l.	3.0 Kv
2	Lime - 900 ppm Polymer - 8 mg/l.	4.8 Kv
3	Lime - 900 ppm Polymer - 8 mg/l.	12.8 Kv
4	Lime - 1500 ppm	3.5 Kv
5	Lime - 1500 ppm	8.3 Kv
6	Lime - 1500 ppm Polymer - 8 mg/l.	5.98 Kv
7	Lime - 1500 ppm	2.2 Kv
8	Lime - 1500 ppm	2.13 Kv
9	Lime - 1500 ppm	5.98 Kh
10	14-20 Frac Sand/ Filter Base	1800 Kv
11	Lime - 1500 ppm	1.45 Kh
12	Lime - 1500 ppm	12.50 Kv
13	Lime - 800 ppm	5.41 Kv
Average	Kv 1500 ppm Lime	5.67 x 10 ⁻⁵ cm/sec.
Average	Kv 900 ppm Lime plus 8 mg/l. Polymer	6.65 x 10 ⁻⁵ cm/sec.
Average	Kh 1500 ppm Lime	3.72 x 10 ⁻⁵ cm/sec.

Notes: 1) All tests for Kv were conducted in permeameter after allowing slurry sufficient time to settle.

2) All tests for Kh were conducted in a dyked flume tank.

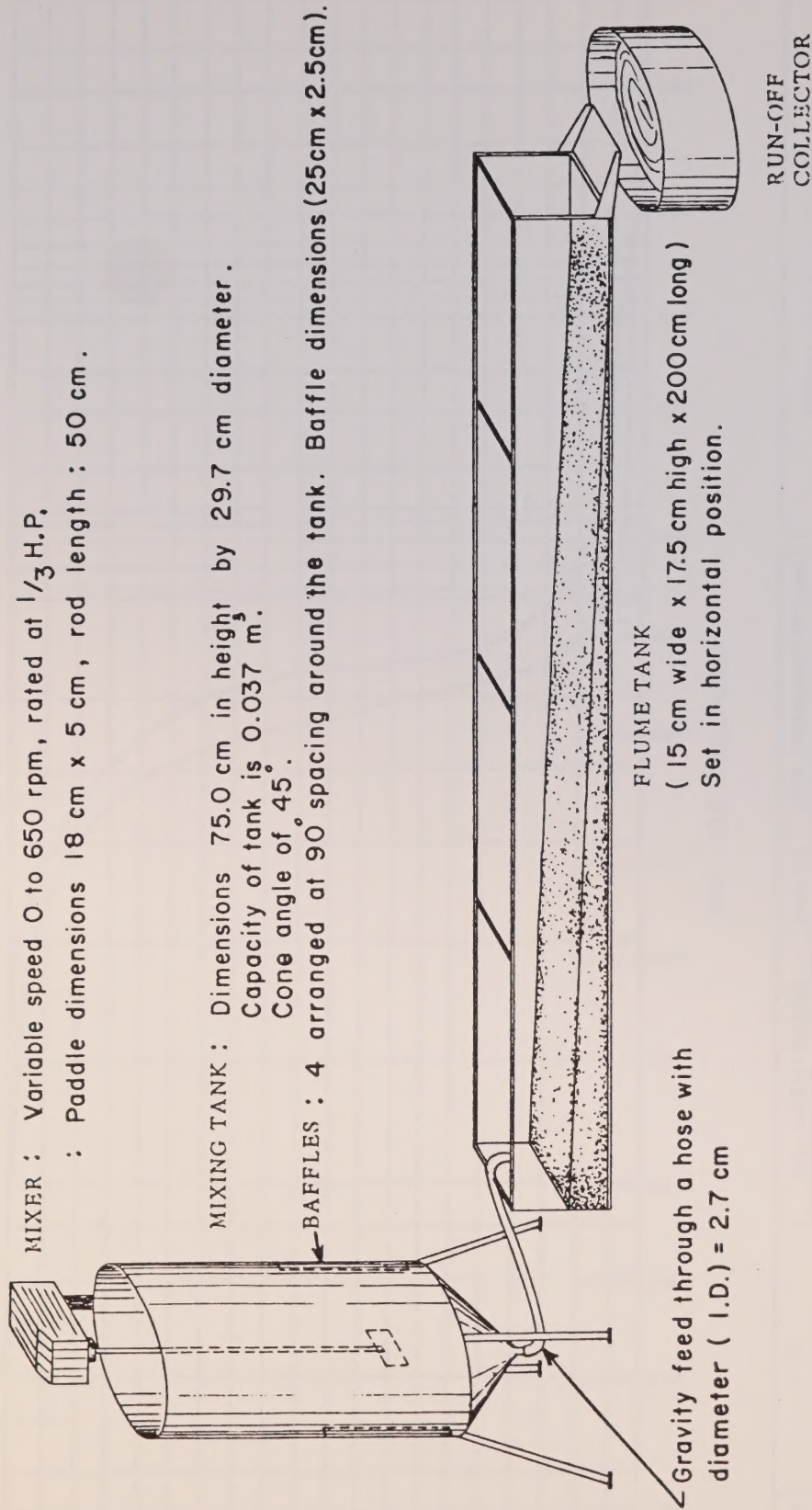
APPENDIX B FIGURES 1 TO 38

TERRACON GEOTECHNIQUE LTD.

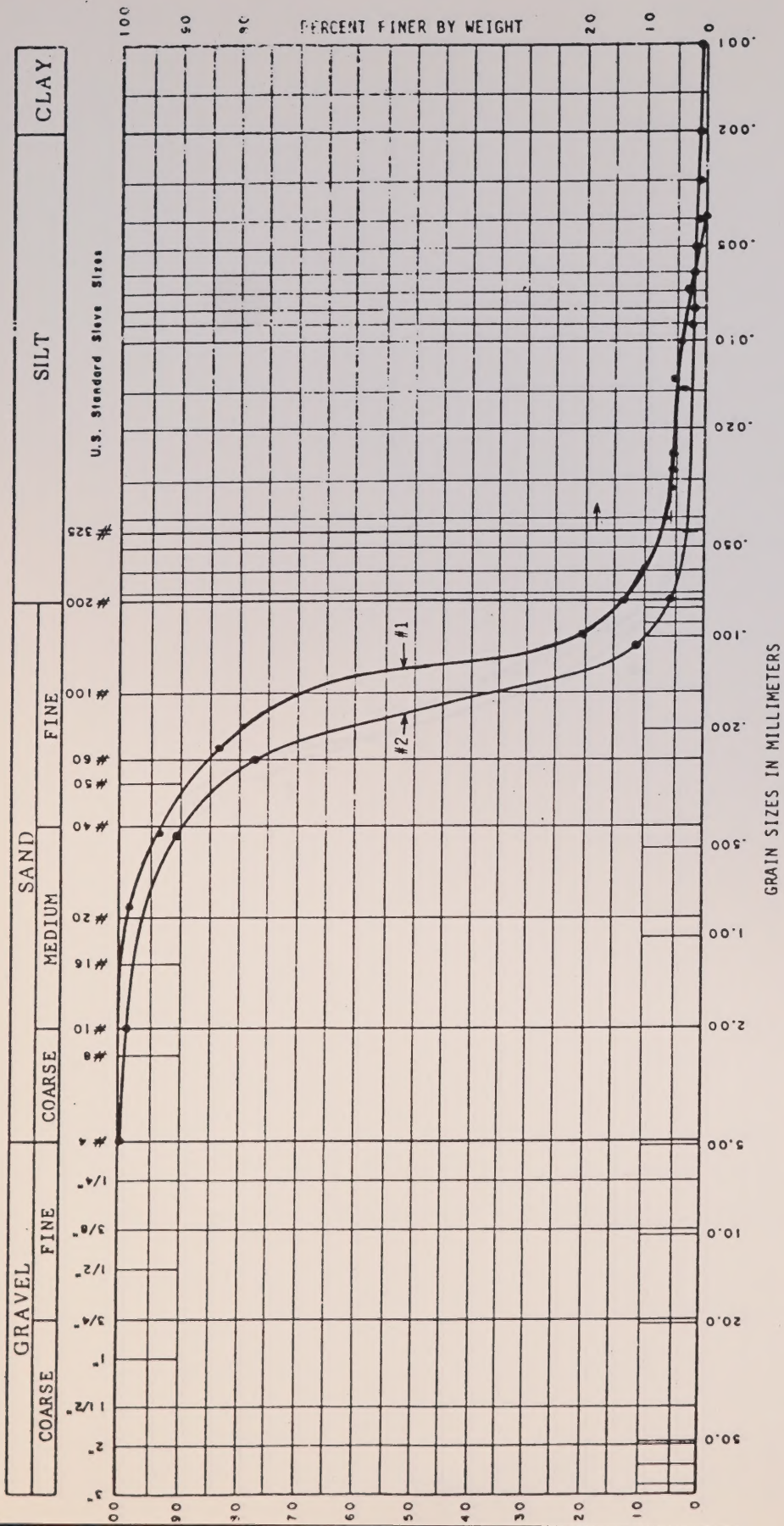
TABLE 6 SUMMARY OF CONSOLIDATED UNDRAINED TRIAXIAL ($\bar{R}$) TESTS

TEST NO.	LIME/POLYMER TREATMENT	e_i	INITIAL DRY DENSITY γ_{d1} (gm/cc)	DRY DENSITY AFTER CONSOLIDATION γ_{dc} (gm/cc)	INITIAL CONFINING STRESS σ'_{3i} (kPa)	MINIMUM CONFINING STRESS σ'_{3m} (kPa)	B-VALUE	
							Initial	Final
1	1500 ppm Lime	0.66	1.50	1.60	1000.0	380.0	0.97	0.70
2	1500 ppm Lime	0.94	1.37	1.39	Estimated at 27.8	25.76	0.99	0.97
3	1500 ppm Lime	0.65	1.52	1.61	75.79	13.09	0.97	0.69
5	1500 ppm Lime	0.66	1.54	1.60	151.58	48.3	0.97	0.64
6	1500 ppm Lime	0.69	1.55	1.57	303.16	101.97	0.89	0.60
8	1500 ppm Lime	0.65	1.57	1.62	55.12	3.86	0.97	0.65'
9	1500 ppm Lime	0.65	1.56	1.62	103.35	7.92	0.94	0.64
12	900 ppm Lime & 8 mg/l Polymer	0.70	1.52	1.57	75.74	10.34	0.72	0.65
15	900 ppm Lime & 8 mg/l Polymer	0.61	1.62	1.65	151.58	59.94	0.99	0.87
16	900 ppm Lime & 8 mg/l Polymer	0.62	1.56	1.64	303.16	139.18	1.00	0.77
17	900 ppm Lime & 8 mg/l Polymer	0.59	1.64	1.67	55.12	28.94	1.00	0.90
18	900 ppm Lime & 8 mg/l Polymer	0.53	1.71	1.74	151.58	94.39	1.00	0.86
19	900 ppm Lime & 8 mg/l Polymer	0.49	1.75	1.78	303.16	192.23	0.99	0.71
20	900 ppm Lime & 8 mg/l Polymer	0.58	1.67	1.68	34.45	18.60	1.00	0.92
21	900 ppm Lime & 8 mg/l Polymer	0.53	1.70	1.74	461.63	338.30	0.91	0.51
22	1500 ppm Lime	0.60	1.65	1.67	34.45	8.96	1.00	0.93
23	1500 ppm Lime	0.50	1.74	1.77	151.58	64.77	1.00	0.78
24	1500 ppm Lime	0.46	1.79	1.82	303.16	186.03	0.93	0.59
25	1500 ppm Lime	0.50	1.75	1.78	303.16	194.30	0.94	0.56
26	1500 ppm Lime	0.62	1.63	1.64	75.79	8.96	0.96	0.86

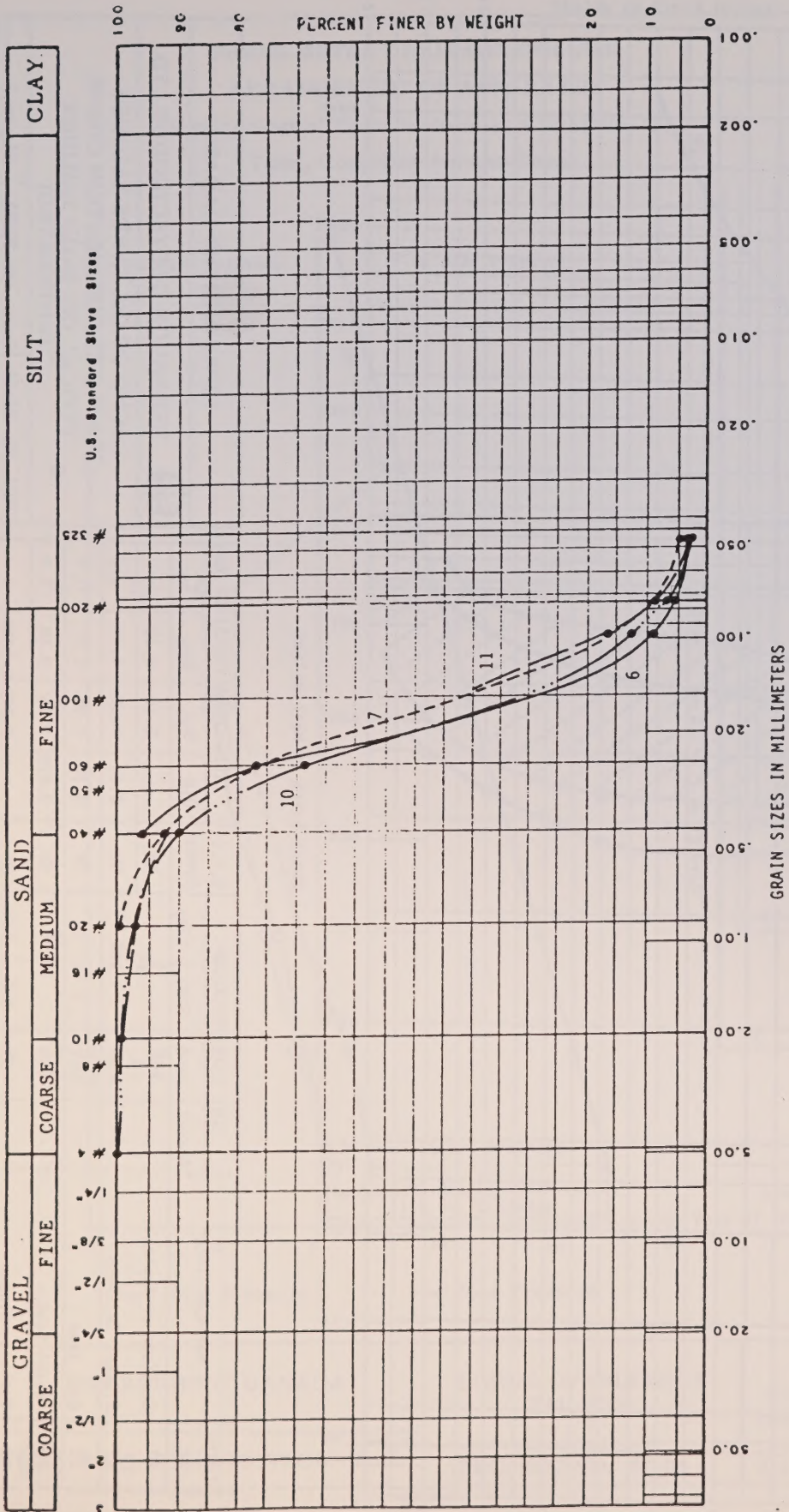
Note: e_i is the Void Ratio at the end of the consolidation stage of the test.
This value is also the Initial Void Ratio for the loading and shearing portion of the triaxial test..



	ENVIRONMENT CANADA	LIMING AND POLYMER ADDITION TO WHOLE OIL SANDS TAILINGS	MIXING TANK AND DEPOSITIONAL FLUME EQUIPMENT LAYOUT
	TERRACON GEOTECHNIQUE	PROJECT 82-06	DATE: NOV/83 FIG. 1

[illegible]

 ENVIRONMENT CANADA	TERRACON GEOTECHNIQUE LTD.	LIMING OF OIL SANDS TAILINGS GRAIN SIZE DISTRIBUTION CURVE LIME TREATMENT	PROJ. NO. 82-06	Date: Nov 20/83	Fig. 3
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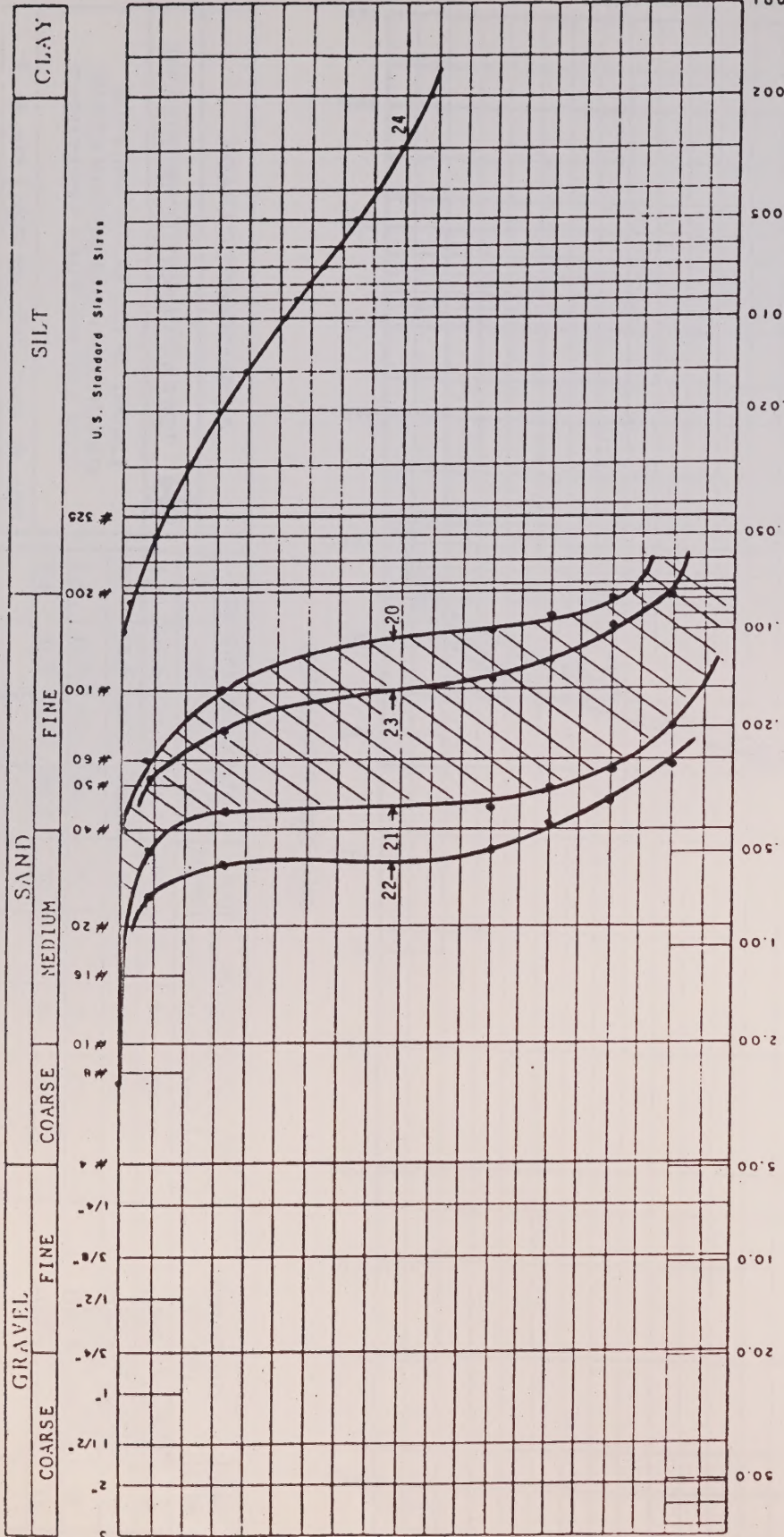
CURVE NO.	LIME/POLYMER TREATMENT	SOIL CLASSIFICATION				SIZE CHARACTERISTICS			
		Gravel	Sand	Silt	Clay	U.S.C. Symbol	D ₁₀	D ₅₀	D ₆₀ Cu
6	Lime - 900 ppm Polymer - 8 mg/l	--	92%	8%	--	SP	0.10	0.20	0.21 2.1
7	Lime - 900 ppm Polymer - 8 mg/l	--	91%	9%	--	SP	0.08	0.18	0.20 2.5
10	Lime - 900 ppm Polymer - 8 mg/l	--	93%	7%	--	SP	0.09	0.20	0.21 2.3
11	Lime - 900 ppm Polymer - 8 mg/l	--	92%	8%	--	SP	0.08	0.18	0.20 2.5

ENVIRONMENT CANADA

TERRACON GEOTECHNIQUE LTD.

LIMING OF OIL SANDS TAILINGS
 GRAIN SIZE DISTRIBUTION CURVE
 LIME AND POLYMER TREATMENT

PROJ. NO. 82-06 DATE: Nov 20/83 Fig. No. 5



CURVE NO.	MATERIAL TYPE	SOIL CLASSIFICATION				U.S.C. Symbol	SIZE CHARACTERISTICS (mm)				
		Gravel	Sand	Silt	Clay		D ₁₀	D ₅₀	D ₆₀	C _u	
20 to 21	Envelope of Typical Oilsand Tailings	--	84% to 100%	0 to 16%	0 to 16%	SM	--	0.10	0.12	--	
22	Dyke Sand -	--	95 to 100%	0 to 5%	5 to 10%	SW	0.20	0.30	0.40	2.0	
23	Beach Sand -	--	90%	10%	10%	SW	0.30	0.55	0.57	1.9	
24	Tailings Sludae	--	2%	47%	51%	CH	--	0.008	0.0042	--	



ENVIRONMENT CANADA

TERRACON GEOTECHNIQUE LTD.

LINING OF OIL SANDS TAILINGS
GRAIN SIZE DISTRIBUTION CURVE
TYPICAL OIL SAND TAILINGS
(UNTREATED)

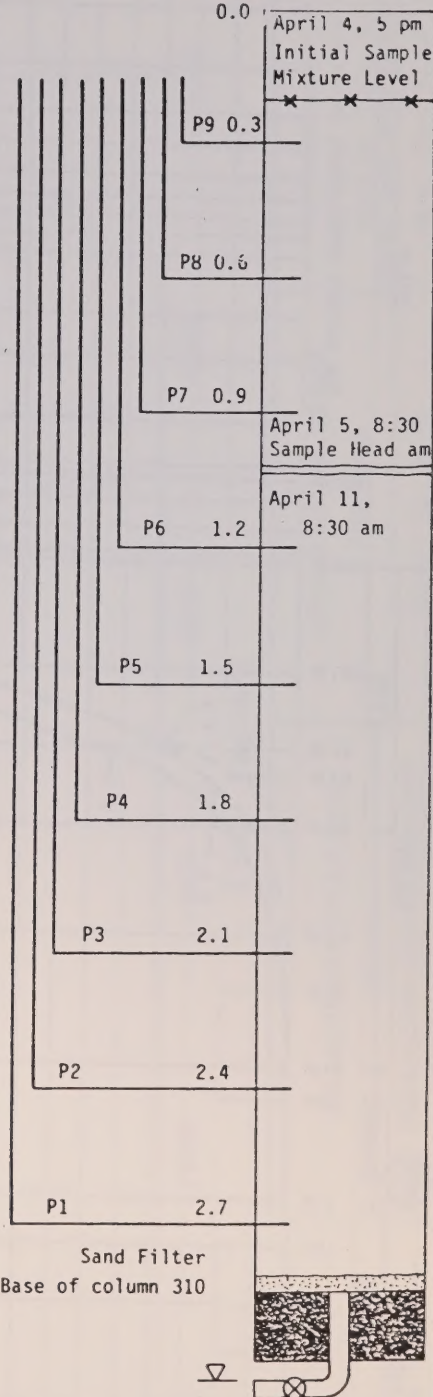
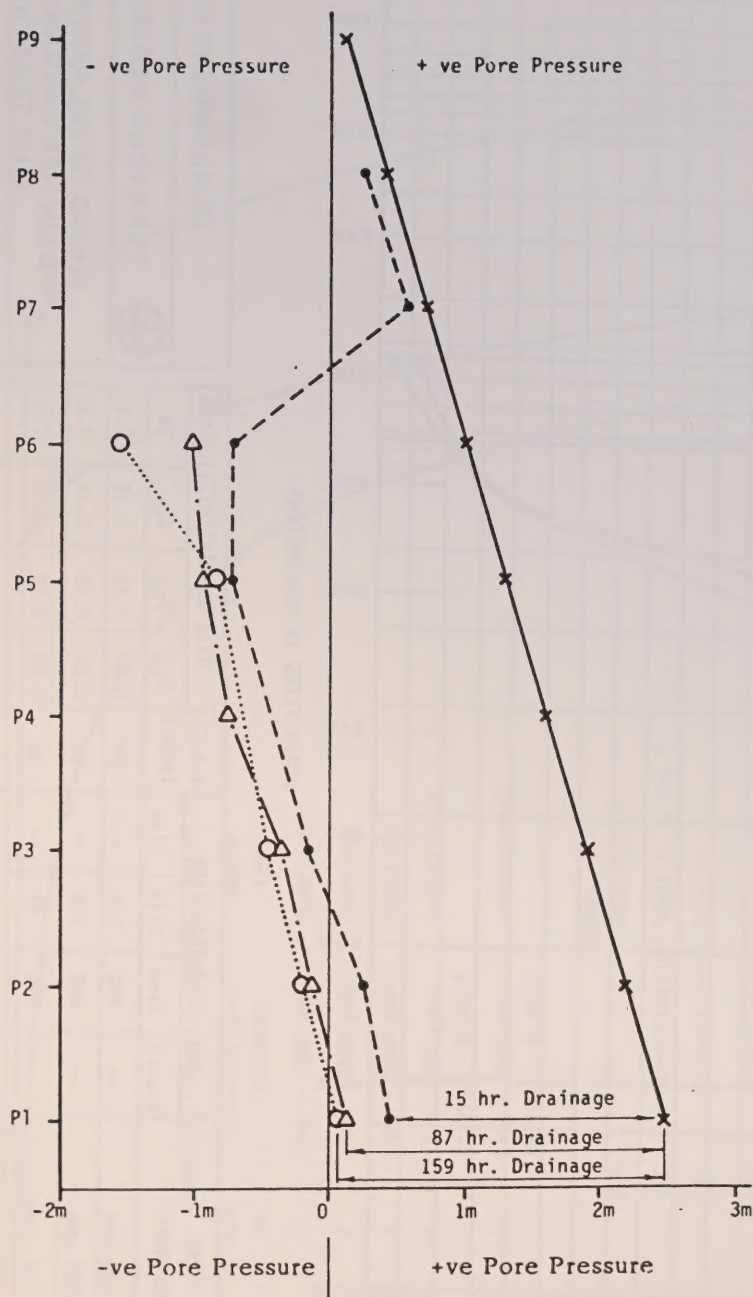
PROJ. NO. 82-06 Date: Nov 20/83 Figure 2

THREE METRE DRAINAGE COLUMN

ARRANGEMENT OF APPARATUS

Development of Pore Pressure as a Function of;
Time, Consolidation and Depth

Vertical Scale
in Metres



ENVIRONMENT CANADA

LIMING OF OILSANDS
TAILINGS

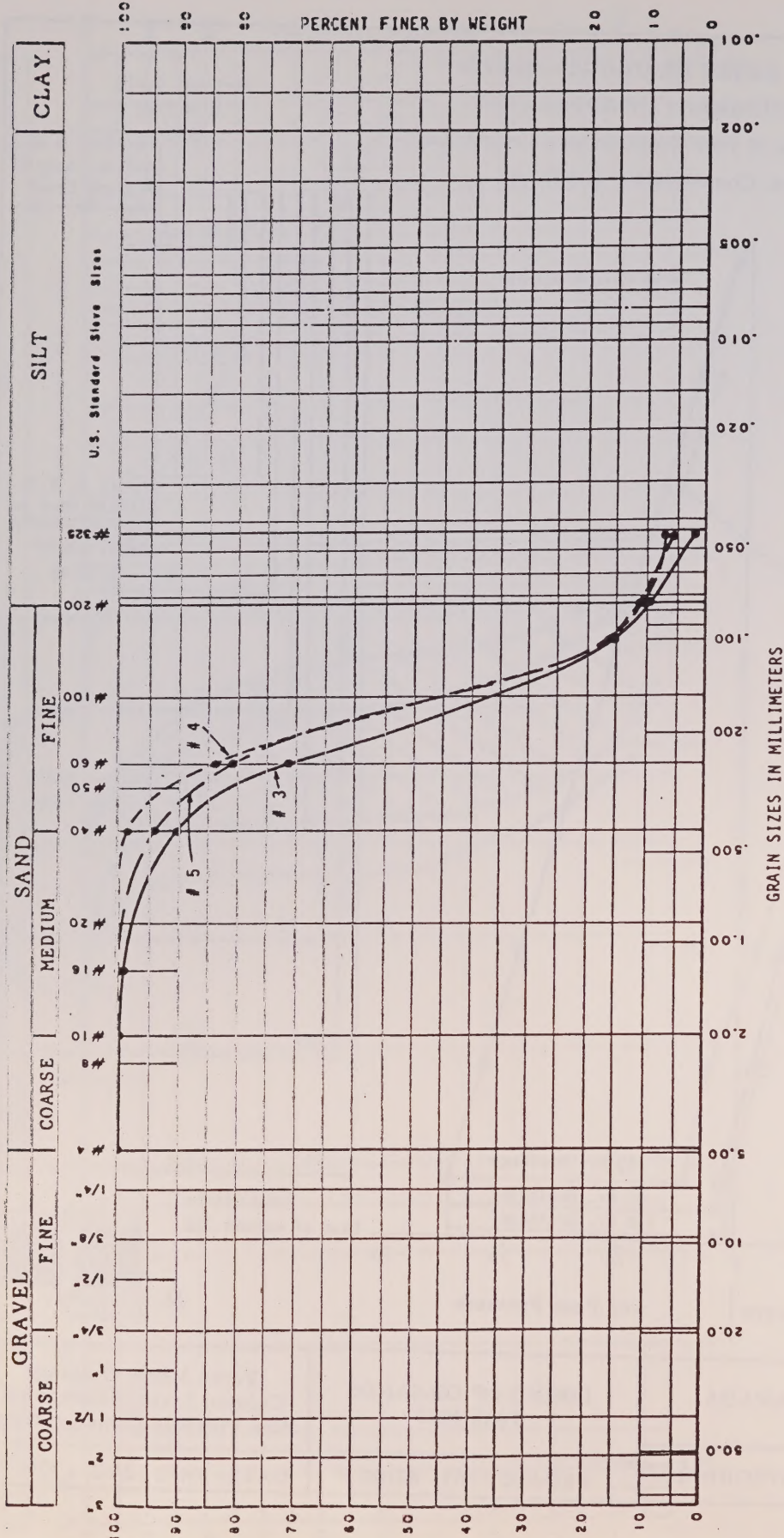
Three Metre Drainage
Column Arrangement with
Pore Pressure Drainage Data



TERRACON GEOTECHNIQUE

PROJECT NO. 82-06

DATE: DEC 12/83 FIG. 7



CURVE NO.	LIME TREATMENT	SOIL CLASSIFICATION				U.S.C. Symbol	SIZE CHARACTERISTICS(mm)			
		Gravel	Sand	Silt	Clay		D ₁₀	D ₅₀	D ₆₀	Cu
4	Lime = 1500 ppm	--	89%	11%	--	SW	0.07	0.16	0.18	2.6
5	Lime = 1500 ppm	--	89%	11%	--	SW	0.07	0.16	0.18	2.6
3	Lime = 1500 ppm	--	91%	9%	--	SW	0.08	0.19	0.20	2.5

ENVIRONMENT CANADA

TERRACON GEOTECHNIQUE LTD.

LIME TREATMENT

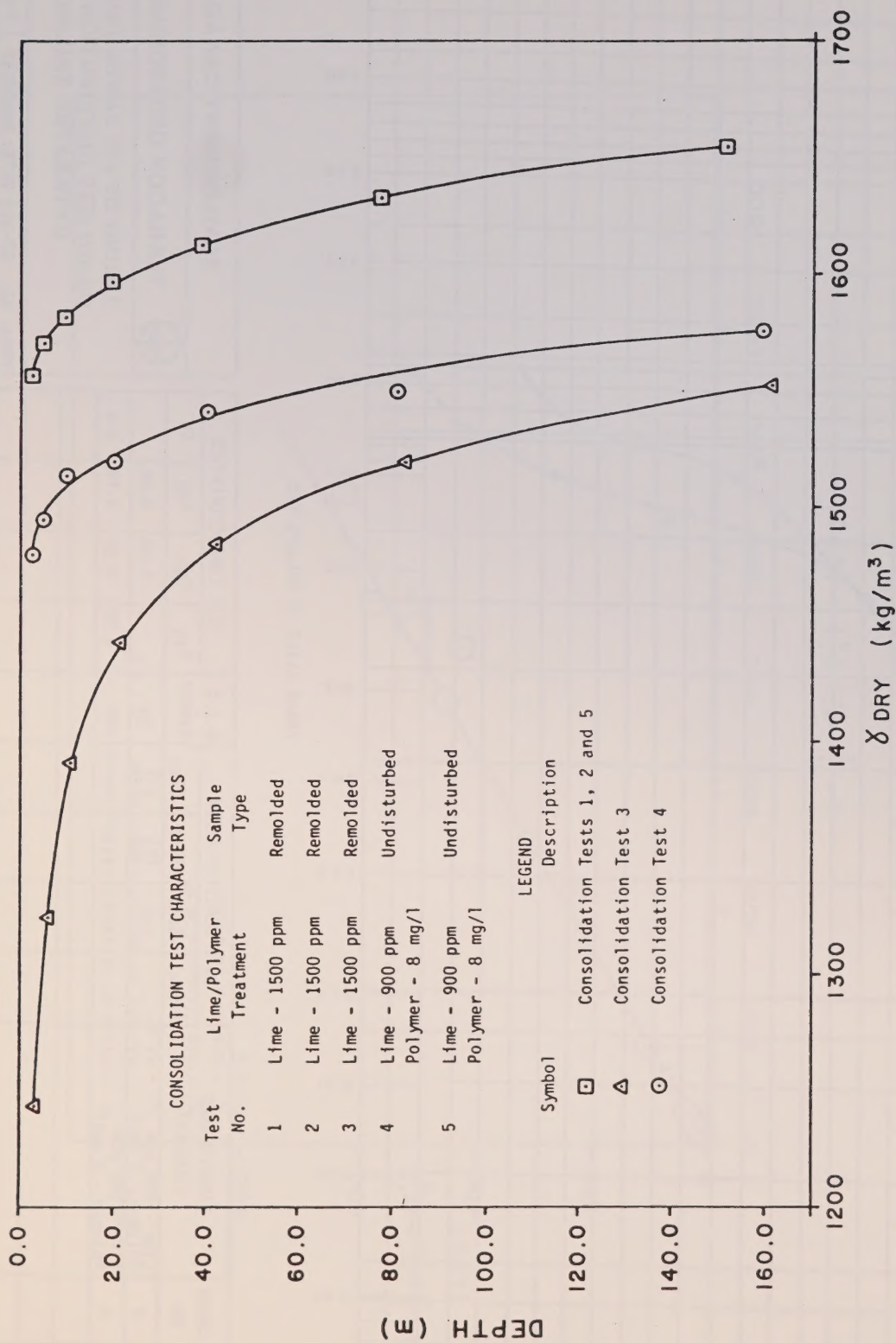
GRAIN SIZE DISTRIBUTION CURVE

TAILINGS OF OIL SANDS

PROJ. NO. 82-06

Date: Nov 20/83

Fig. 4



Predicted Dry Density as a
Function of Depth for Treated
Whole Oil Sands Tailings
(Based upon Consolidation Curves)

LIMING OF OIL SANDS
TAILINGS

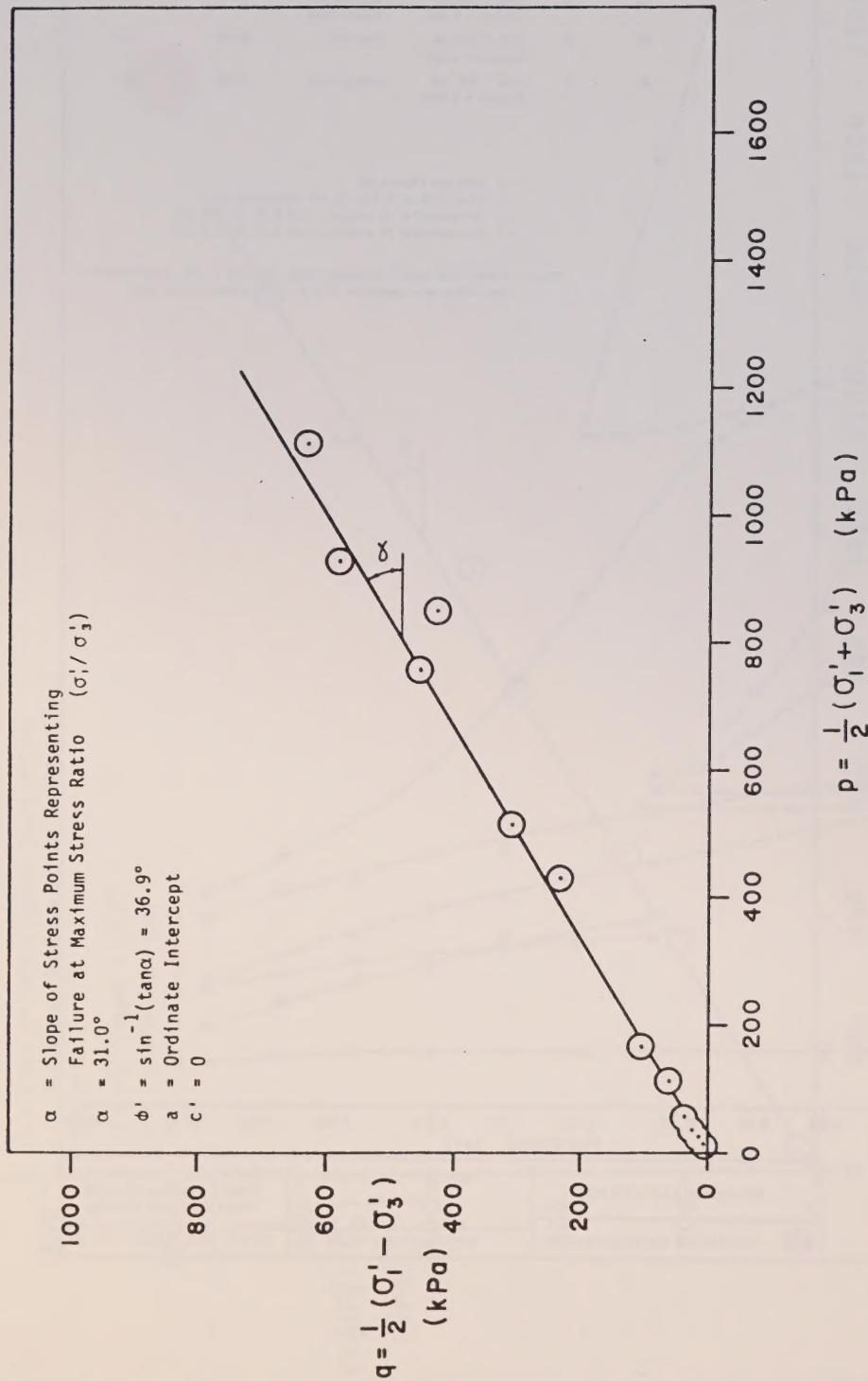
PROJECT NO. 82-06

ENVIRONMENT CANADA



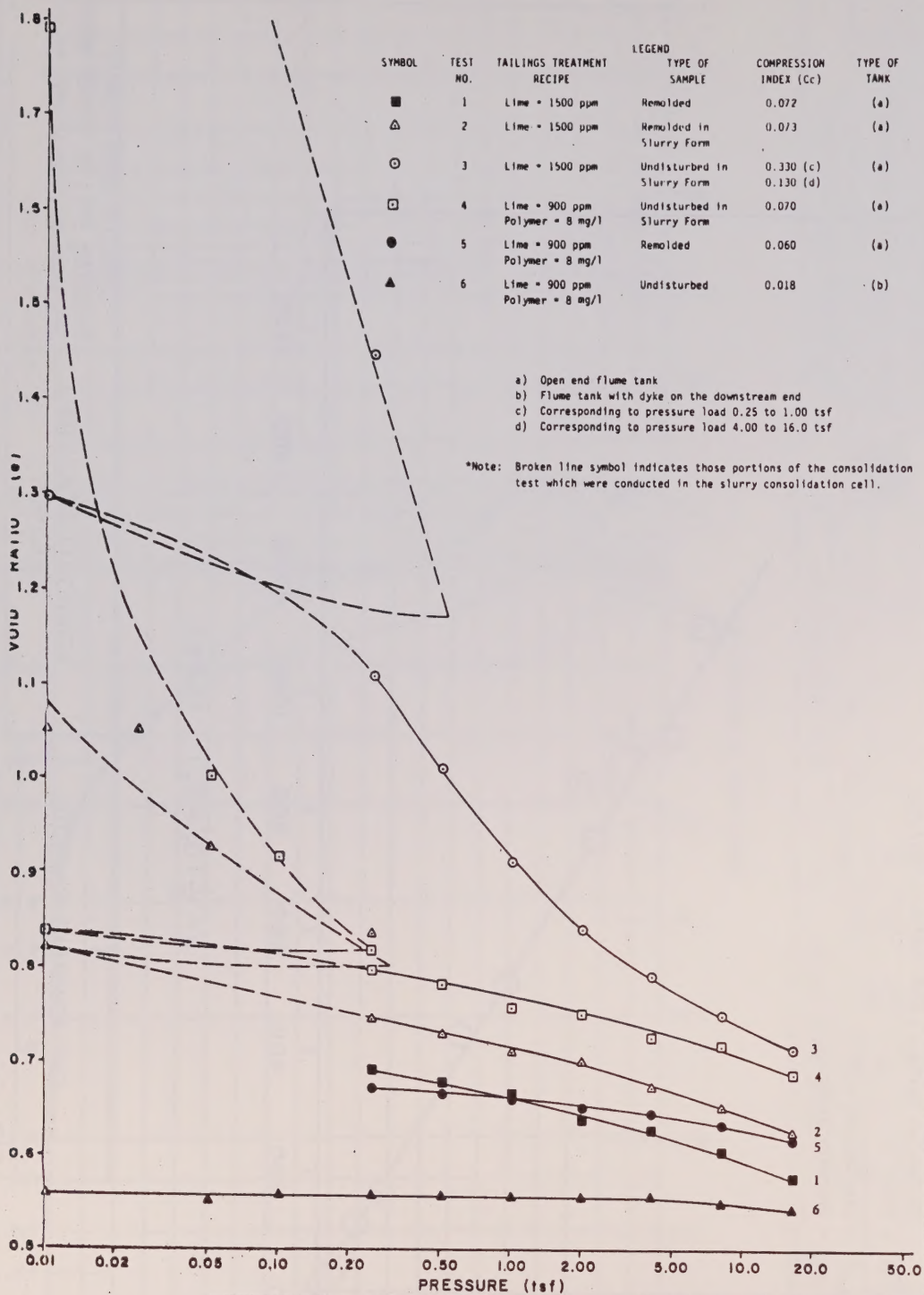
TERRACON GEOTECHNIQUE

Date: Nov. 18/83 Fig. 9



EFFECTIVE SHEAR STRENGTH PARAMETERS FOR LIME TREATED WHOLE OILSANDS TAILINGS AT MAX σ'_1 / σ'_3	LIMITING OF OILSANDS TAILINGS	ENVIRONMENT CANADA
DATE: NOV 20/83	PROJECT NO: 82-06	TERRACON GEOTECHNIQUE





ENVIRONMENT CANADA	LINING OF OIL SANDS TAILINGS	Consolidation Curves for Lime & Polymer Treated Whole Oil Sands Tailings
 TERRACON GEOTECHNIQUE	PROJECT NO: 82-06	DATE: NOV. 18/83 FIG. 8

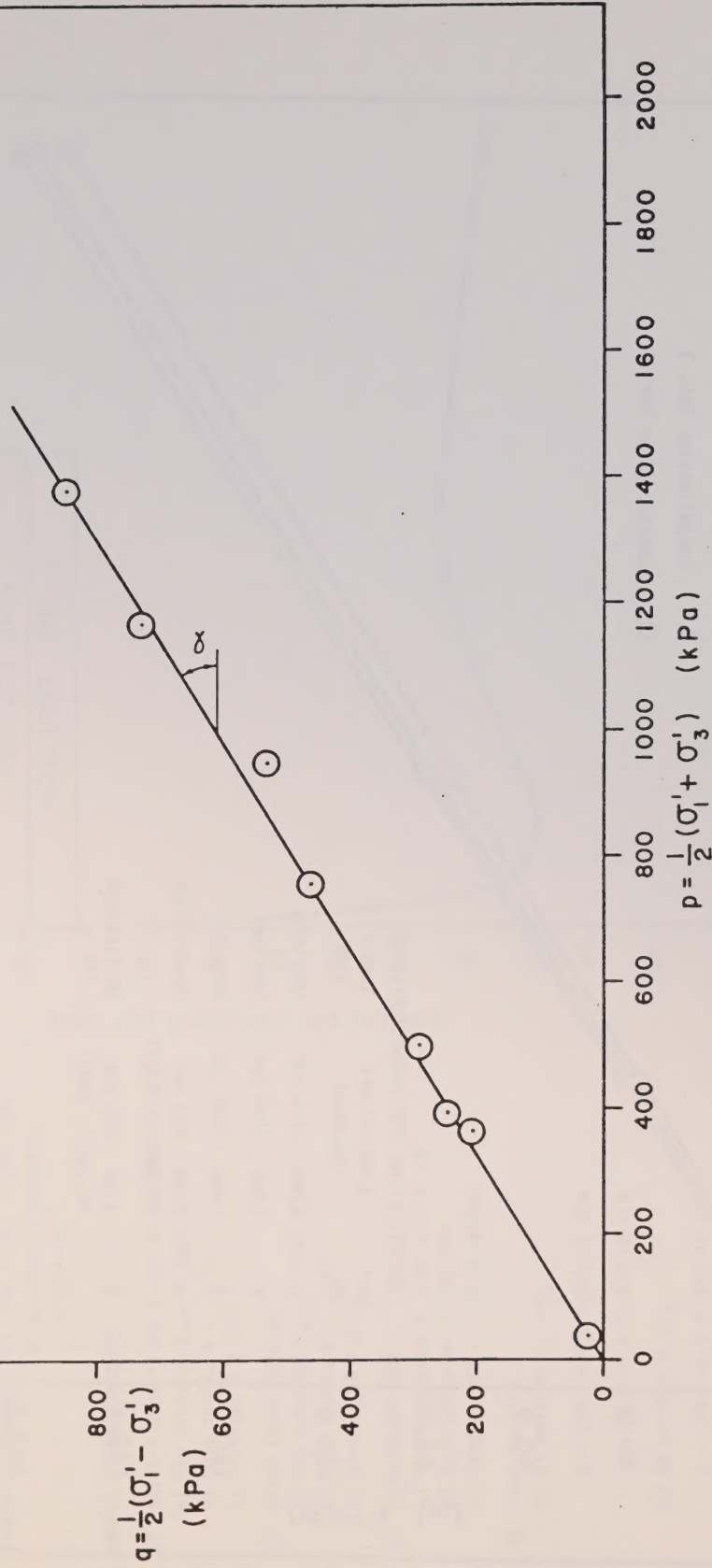
α = Slope of Stress Points Representing Failure at Maximum Stress Ratio (σ'_1/σ'_3)

$\alpha = 31.4^\circ$

$\phi' = \sin^{-1}(\tan \alpha) = 37.6^\circ$

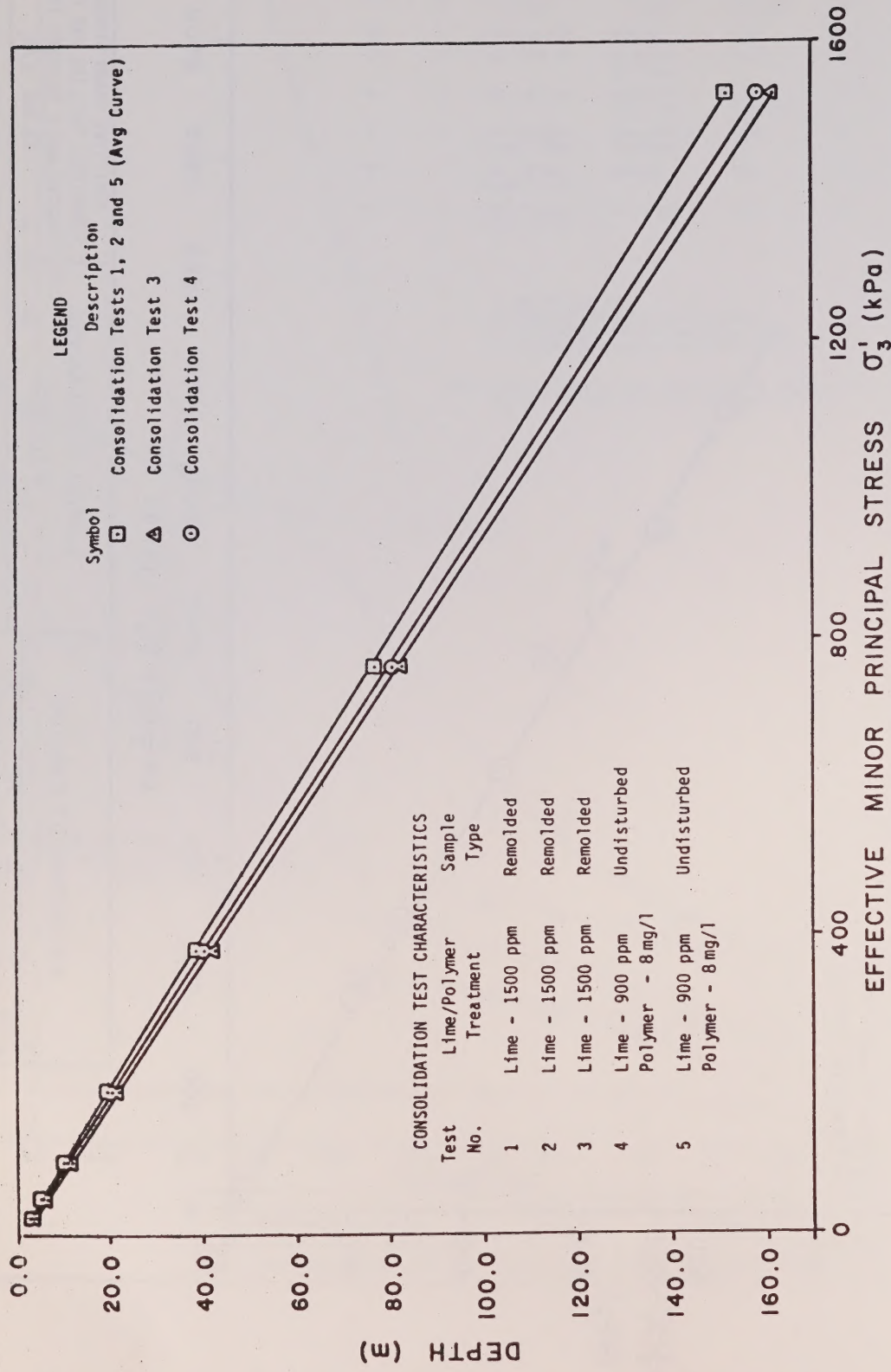
a = Ordinate Intercept

$c' = 0$



ENVIRONMENT CANADA	LIMING OF OILSANDS TAILINGS	EFFECTIVE SHEAR STRENGTH PARAMETERS FOR LIME AND POLYMER TREATED WHOLE OILSANDS TAILINGS AT MAX σ'_1/σ'_3
	TERRACON GEOTECHNIQUE	DATE: NOV 20/83 FIG NO. 13





ENVIRONMENT CANADA		LIMING OF OIL SANDS TAILINGS	PREDICTED EFFECTIVE MINOR PRINCIPAL STRESS (σ'_3) AS A FUNCTION OF DEPTH FOR TREATED WHOLE OIL SANDS TAILINGS
TERRACON GEOTECHNIQUE		PROJECT NO. 82-06	Date: Nov. 18/83 Fig. 10

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 1 (Thurber)

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810(1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
Al10) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1500 kg/m³
- b) Void ratio, e = 0.78
- c) B-value, B = 0.97

2) After Consolidation

- a) Dry density, γ_{dry} = 1600 kg/m³
- b) Void ratio, e = 0.66
- c) B-value, B = 0.70

3) Test Conditions

- a) Specimen size = 3.86 x 7.59 cm³
- b) Back pressure = 700 kPa
- c) Strain rate = 0.16 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 985.54 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 467.75 \text{ kPa}$
- b) At maximum σ_1/σ_3
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 853.62 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 425.47 \text{ kPa}$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

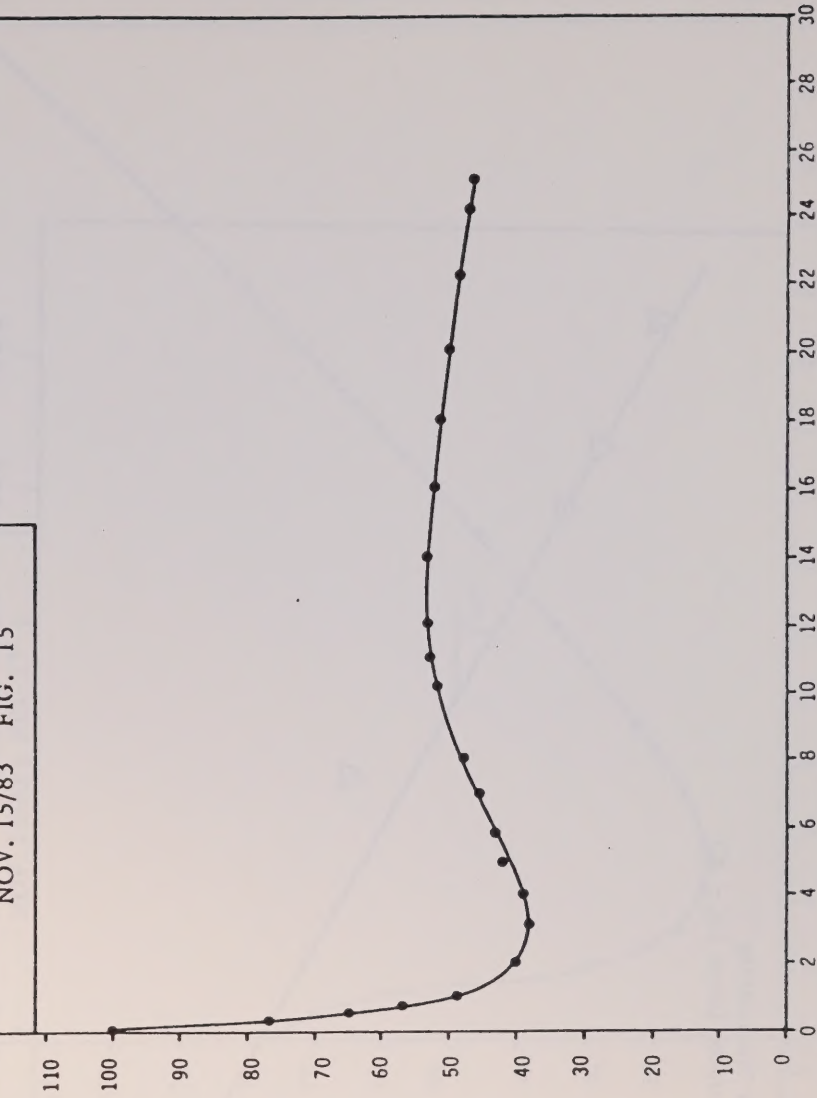


TERRACON GEOTECHNIQUE

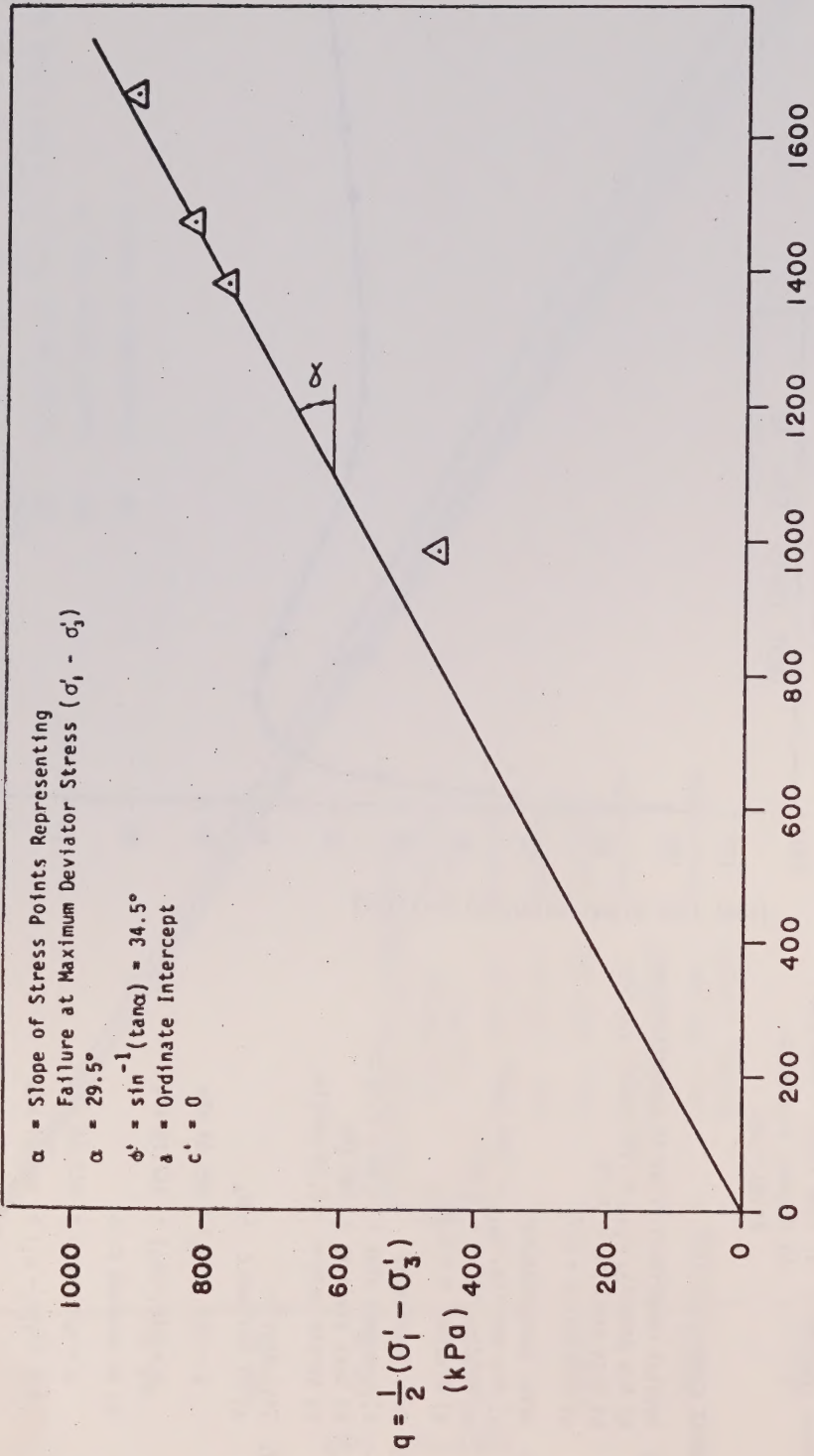
PROJECT 82-06

NOV. 15/83 FIG. 15

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



AXIAL STRAIN, %



ENVIRONMENT CANADA	LIMITING OF OILSANDS TAILINGS	EFFECTIVE SHEAR STRENGTH PARAMETERS FOR LIME TREATED WHOLE OILSANDS TAILINGS AT MAX
 TERRACON GEOTECHNIQUE	PROJECT NO: 82-06	DATE: NOV 20/83 FIG 12

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 3

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810 (1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1520 kg/m³
- b) Void ratio, e = 0.68
- c) B-value, B = 0.97

2) After Consolidation

- a) Dry density, γ_{dry} = 1610 kg/m³
- b) Void ratio, e = 0.65
- c) B-value, B = 0.69

3) Test Conditions

- a) Specimen size = 3.74 x 7.81 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.15 mm/min

4) Test Results

a) At maximum $\sigma_1 - \sigma_3$

$$p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$$

$$q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$$

b) At maximum σ_1/σ_3

$$p = \frac{1}{2}(\sigma_1 + \sigma_3) = 38.44 \text{ kPa}$$

$$q = \frac{1}{2}(\sigma_1 - \sigma_3) = 25.35 \text{ kPa}$$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

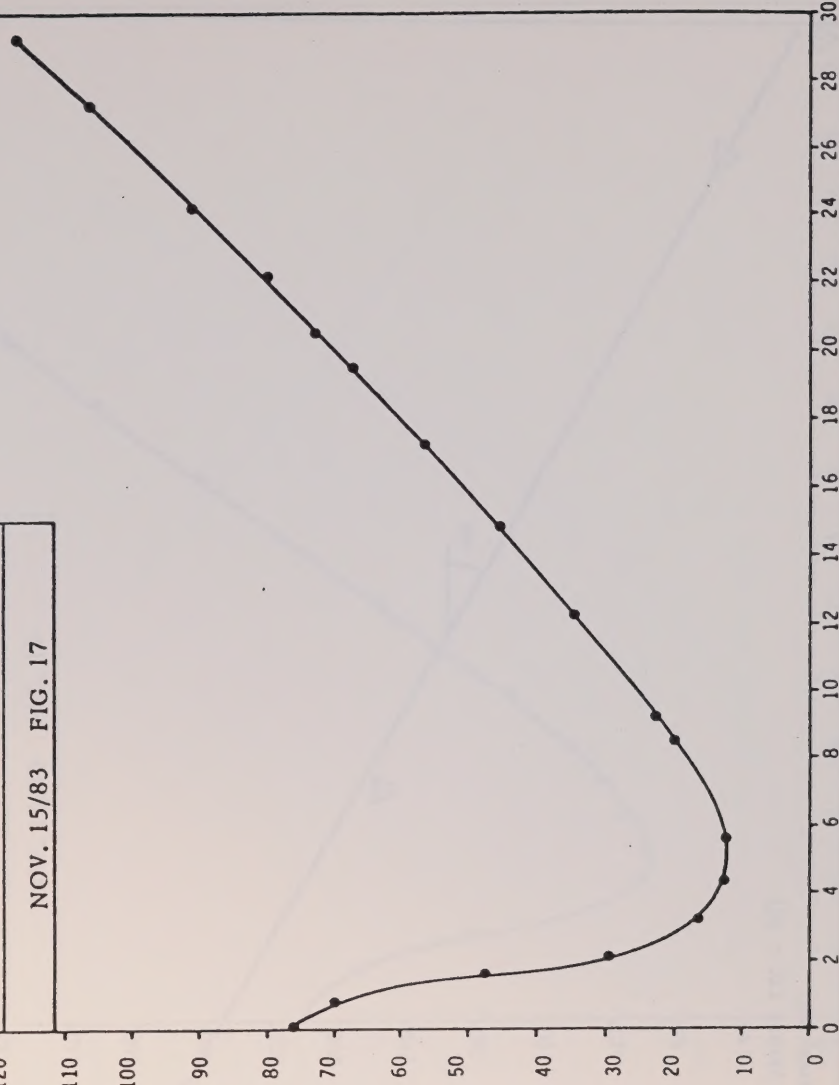


TERRACON GEOTECHNIQUE

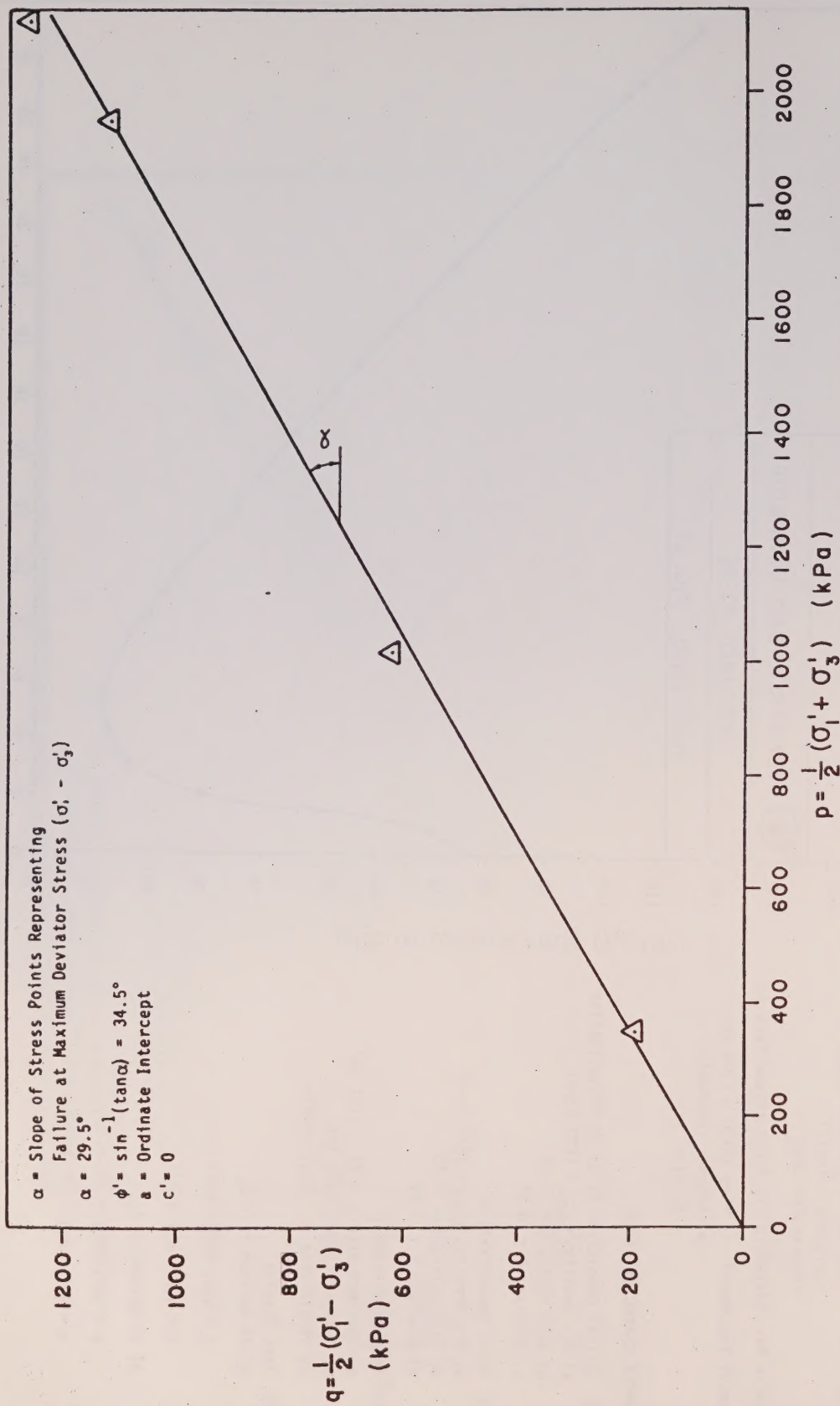
PROJECT 82-06

NOV. 15/83 FIG. 17

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



AXIAL STRAIN, %



ENVIRONMENT CANADA  TERRACON GEOTECHNIQUE	LIMING OF OILSANDS TAILINGS	EFFECTIVE SHEAR STRENGTH PARAMETERS FOR LIME AND POLYMER TREATED WHOLE OILSANDS TAILINGS AT MAX $\sigma'_1 - \sigma'_3$
		DATE: NOV 20/83 FIG 14

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 6

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810 (1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1550 kg/m³
- b) Void ratio, e = 0.72
- c) B-value, B = 0.96

2) After Consolidation

- a) Dry density, γ_{dry} = 1570 kg/m³
- b) Void ratio, e = 0.69
- c) B-value, B = 0.60

3) Test Conditions

- a) Specimen size = 3.74 x 7.87 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.15 mm/min

4) Test Results

- a) At maximum σ_1 - σ_3 ,

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = \text{nil}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = \text{nil}$$

- b) At maximum σ_1/σ_3 ,

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 1108.06 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 638.92 \text{ kPa}$$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

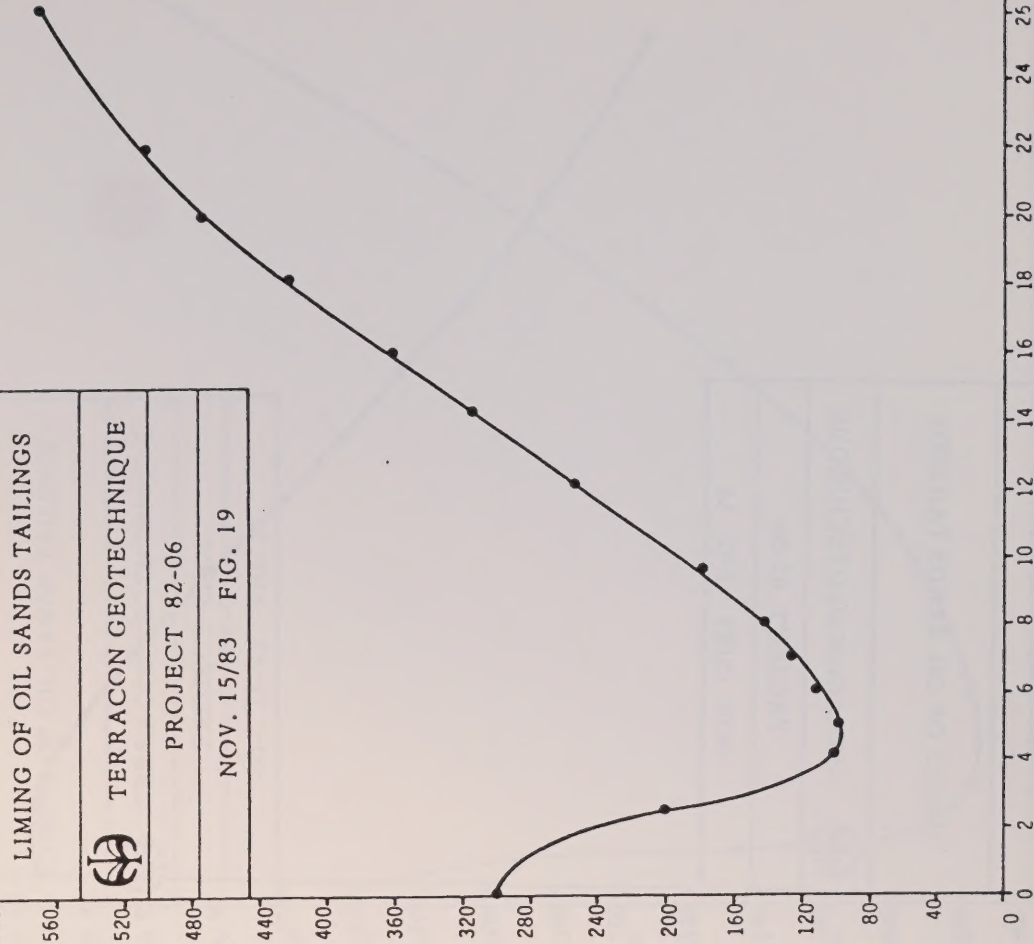


TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 19

EFFECTIVE CONFINING STRESS (σ_3') (kPa)



AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 2 (Thurber)

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83321/83225 (Flume Tank 10)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1370 kg/m³
- b) Void ratio, e = 0.94
- c) B-value, B = 0.99

2) After Consolidation

- a) Dry density, γ_{dry} = 1230 kg/m³
- b) Void ratio, e = 1.16
- c) B-value, B = 0.97

3) Test Conditions

- a) Specimen size = 3.81 x 8.13 cm³
- b) Back pressure = 700 kPa
- c) Strain rate = 0.16 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3)$ = Peak Deviator Stress
 $q = \frac{1}{2}(\sigma_1 - \sigma_3)$ = Not Achieved
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3)$ = 109.76 kPa
 $q = \frac{1}{2}(\sigma_1 - \sigma_3)$ = 61.13 kPa

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 16

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 9

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810(1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
Allio) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1560 kg/m³
- b) Void ratio, e = 0.70
- c) B-value, B = 0.96

2) After Consolidation

- a) Dry density, γ_{dry} = 1620 kg/m³
- b) Void ratio, e = 0.65
- c) B-value, B = 0.64

3) Test Conditions

- a) Specimen size = 3.74 x 7.85 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 27.64 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 16.75 \text{ kPa}$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



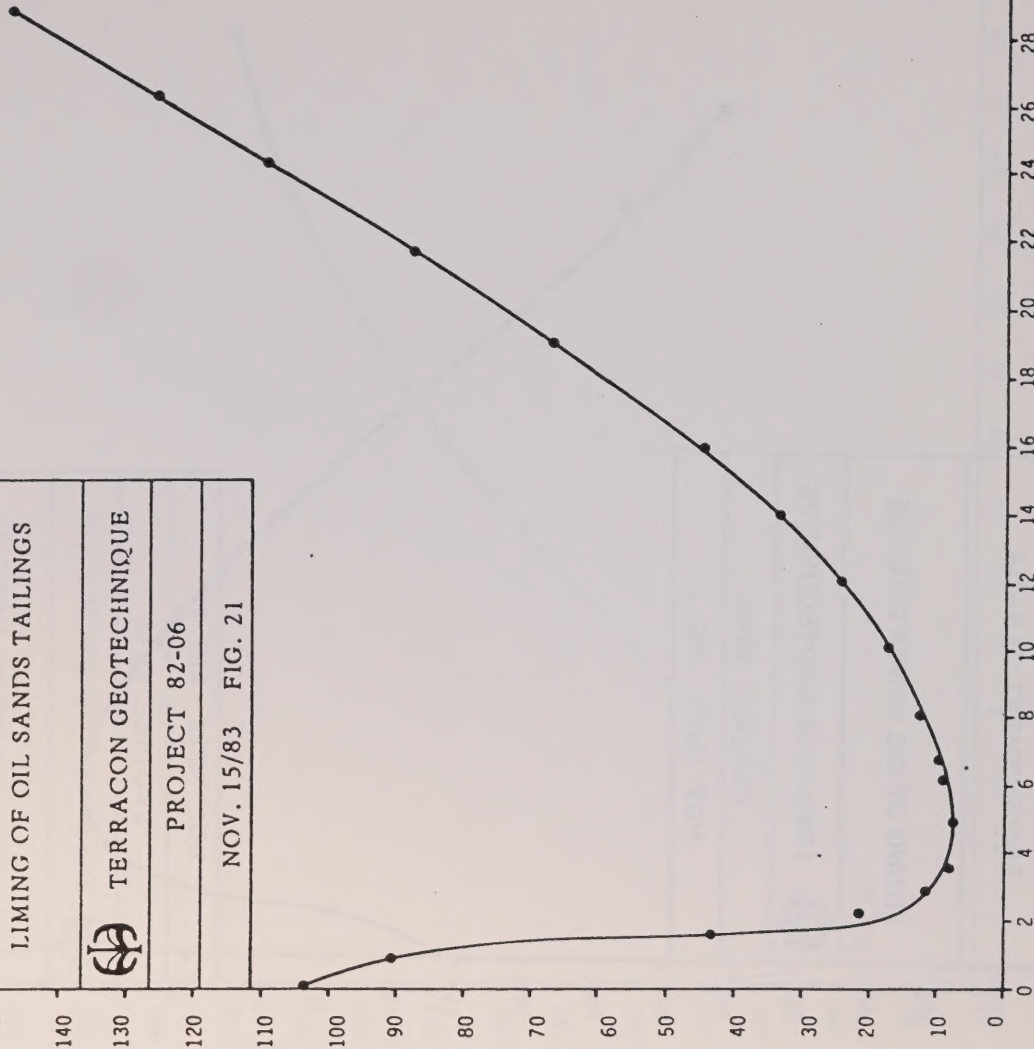
TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 21

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

AXIAL STRAIN, %



EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 5

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810 (1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1540 kg/m³
- b) Void ratio, e = 0.72
- c) B-value, B = 0.99

2) After Consolidation

- a) Dry density, γ_{dry} = 1600 kg/m³
- b) Void ratio, e = 0.66
- c) B-value, B = 0.64

3) Test Conditions

- a) Specimen size = 3.74 x 7.84 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.15 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 430.82 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 231.7 \text{ kPa}$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

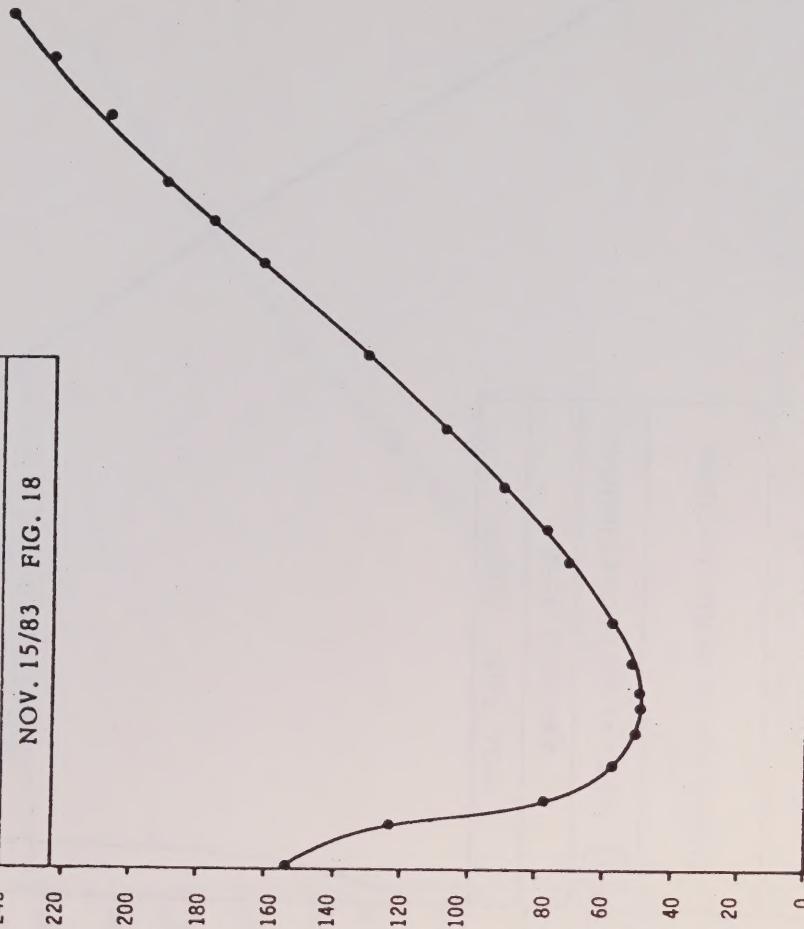


TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 18

EFFECTIVE CONFINING STRESS (σ_3') (kPa)



AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 15

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
All0) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1620 kg/m³
- b) Void ratio, e = 0.64
- c) B-value, B = 0.99

2) After Consolidation

- a) Dry density, γ_{dry} = 1650 kg/m³
- b) Void ratio, e = 0.61
- c) B-value, B = 0.87

3) Test Conditions

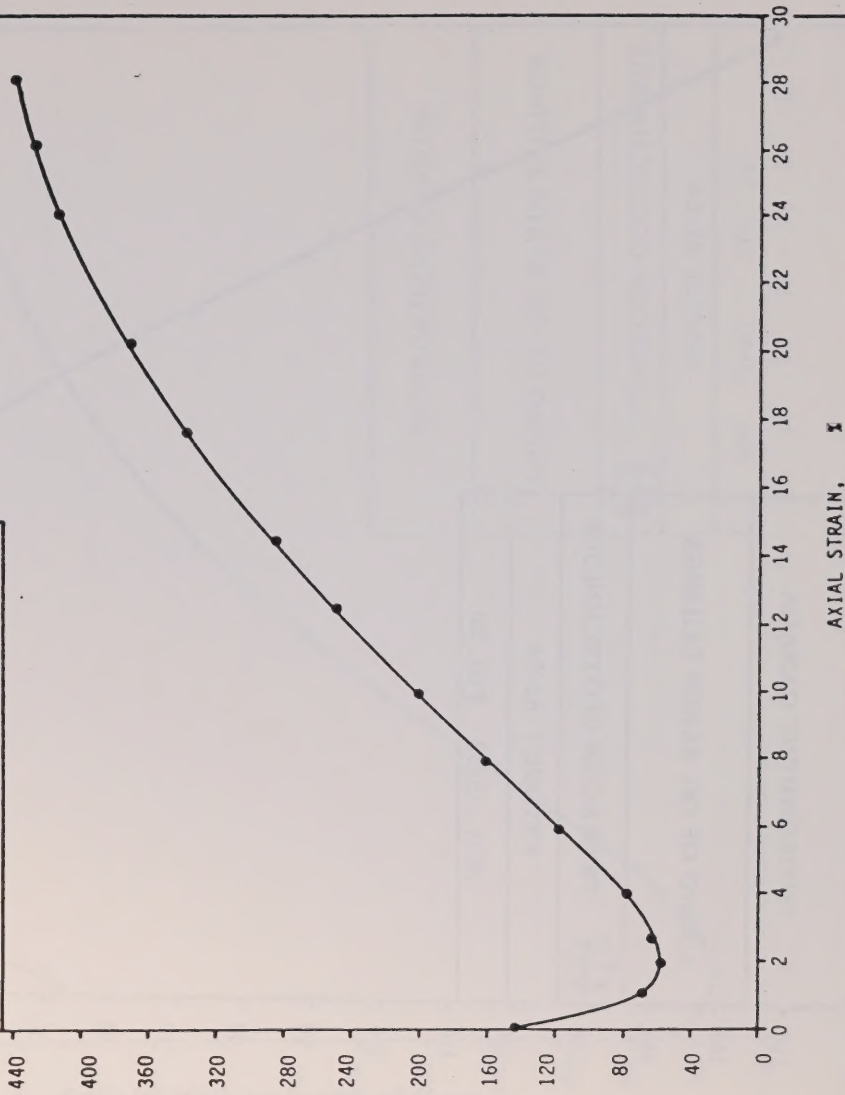
- a) Specimen size = 3.74 x 7.85 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 357.92 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 208.41 \text{ kPa}$

640	ENVIRONMENT CANADA
600	
560	LIMING OF OIL SANDS TAILINGS
520	 TERRACON GEOTECHNIQUE
480	PROJECT 82-06
440	NOV. 15/83 FIG. 23

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 8

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810(1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1570 kg/m³
- b) Void ratio, e = 0.70
- c) B-value, B = 0.97

2) After Consolidation

- a) Dry density, γ_{dry} = 1620 kg/m³
- b) Void ratio, e = 0.65
- c) B-value, B = 0.65

3) Test Conditions

- a) Specimen size = 3.74 x 7.85 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$

$$p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$$

$$q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$$

- b) At maximum σ_1/σ_3

$$p = \frac{1}{2}(\sigma_1 + \sigma_3) = 13.13 \text{ kPa}$$

$$q = \frac{1}{2}(\sigma_1 - \sigma_3) = 9.27 \text{ kPa}$$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

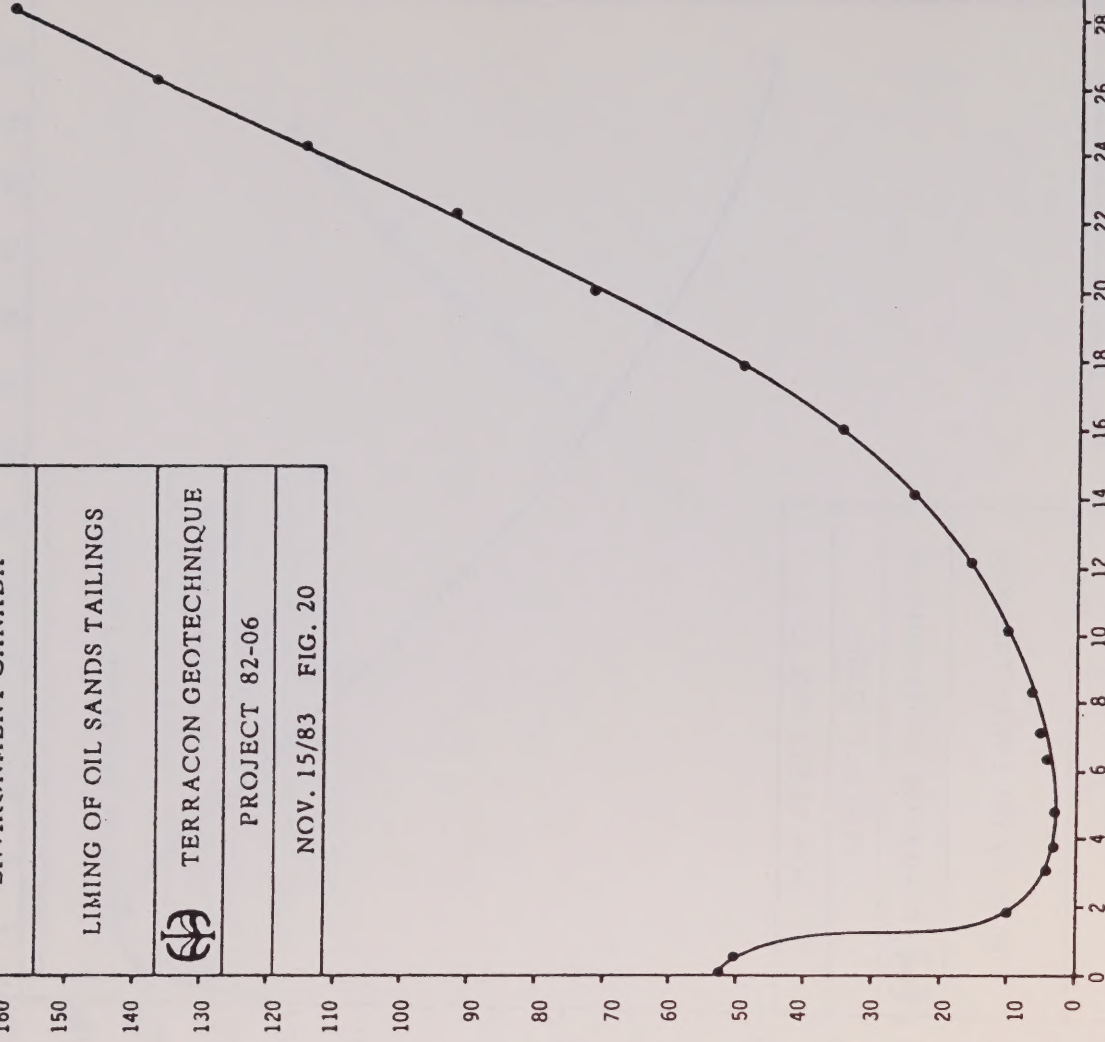


TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 20

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 17

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
Allo) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, γ_{dry} = 1640 kg/m³
- b) Void ratio, e = 0.62
- c) B-value, B = 1.0

2) After Consolidation

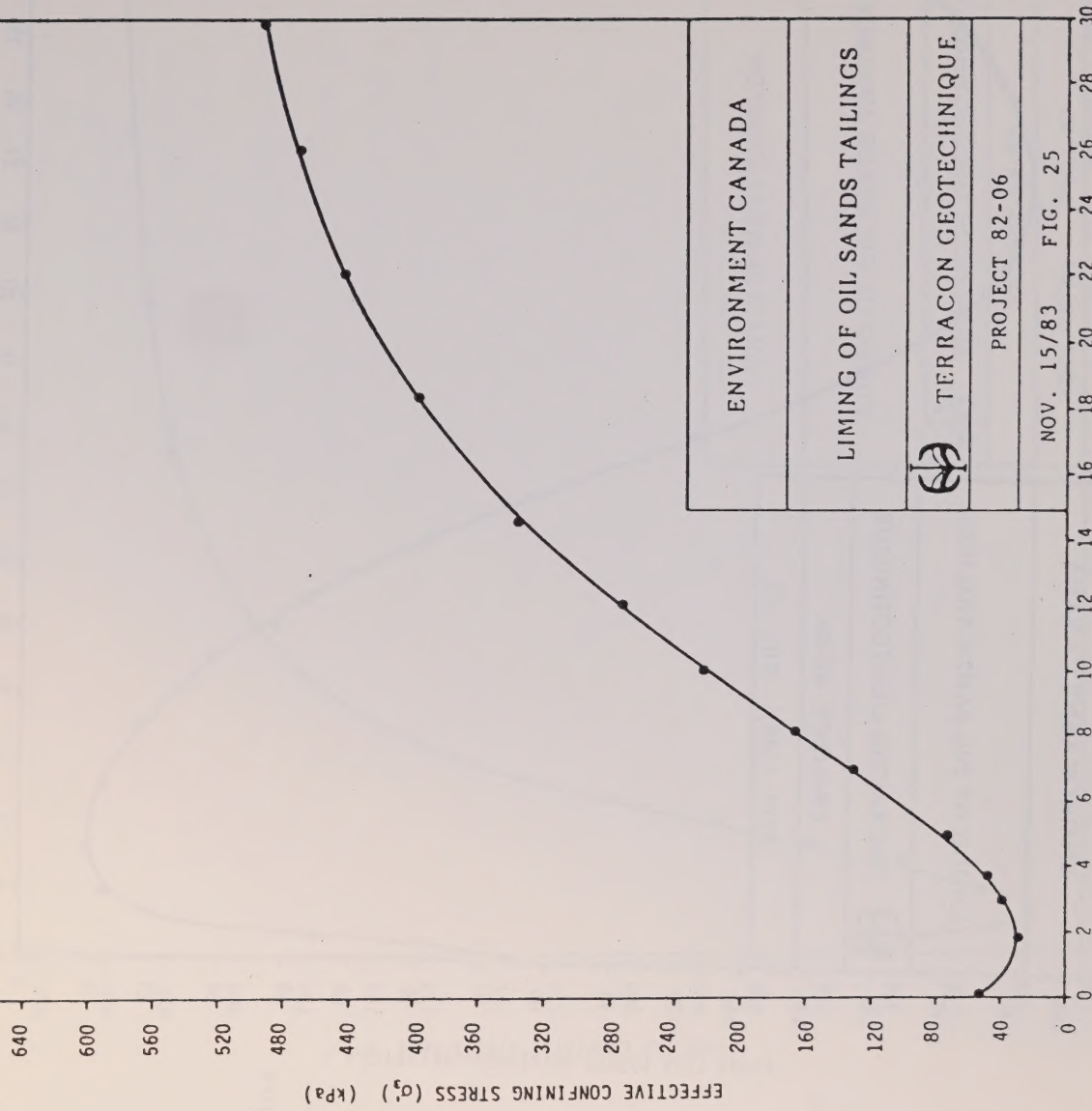
- a) Dry density, γ_{dry} = 1670 kg/m³
- b) Void ratio, e = 0.59
- c) B-value, B = 0.9

3) Test Conditions

- a) Specimen size = 3.74 x 7.90 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{3}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{3}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{3}(\sigma_1 + \sigma_3) = 498.50 \text{ kPa}$
 $q = \frac{1}{3}(\sigma_1 - \sigma_3) = 294.56 \text{ kPa}$



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 25

AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 12

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
All0) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, $\gamma_{dry} = 1520 \text{ kg/m}^3$
- b) Void ratio, $e = 0.75$
- c) B-value, $B = 1.0$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1570 \text{ kg/m}^3$
- b) Void ratio, $e = 0.70$
- c) B-value, $B = 0.65$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.85 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 344.86 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 191.22 \text{ kPa}$
- b) At maximum σ_1/σ_3
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 33.92 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 22.21 \text{ kPa}$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



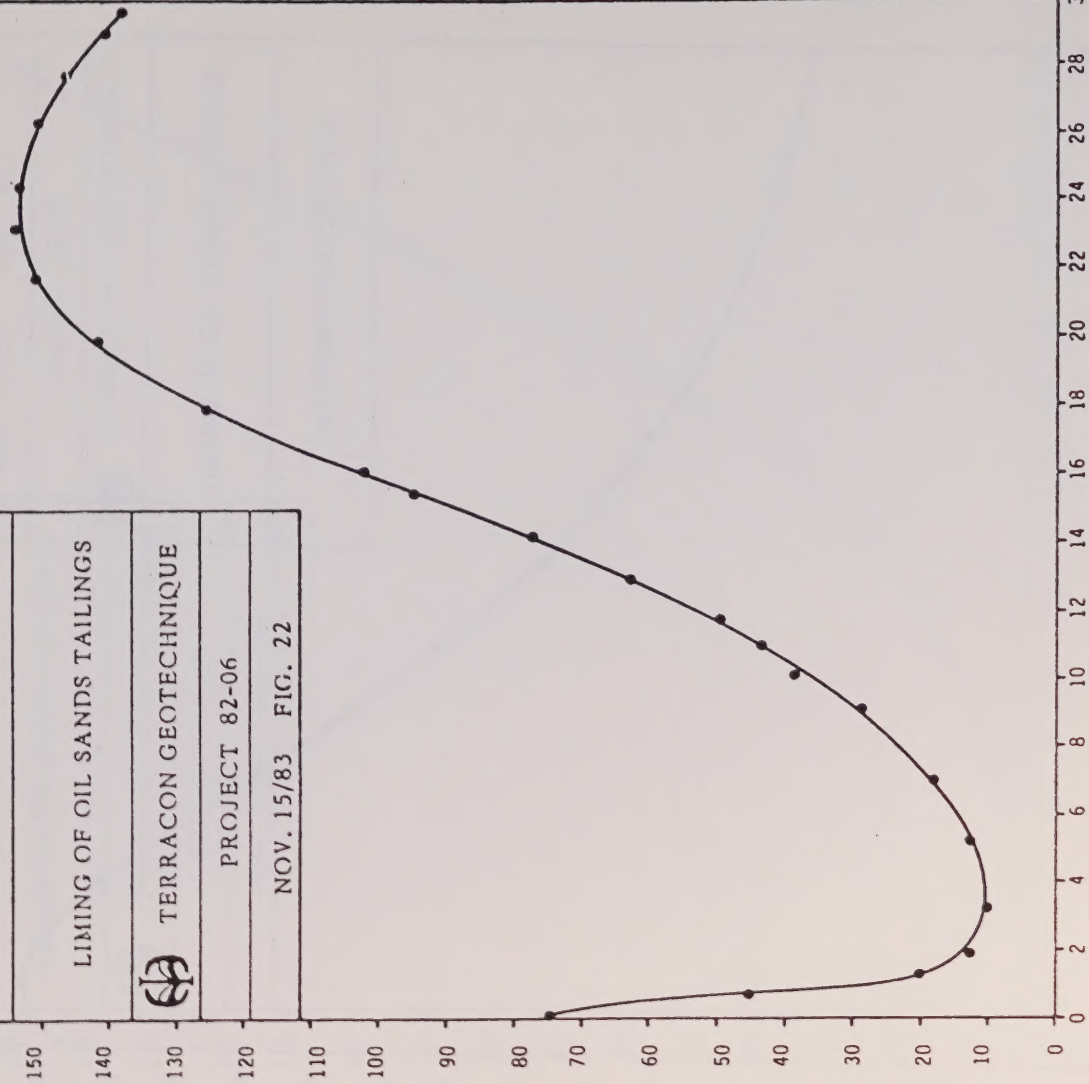
TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 22

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

AXIAL STRAIN, %



EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 19

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
A110) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to

Consolidation

- a) Dry density, $\gamma_{dry} = 1750 \text{ kg/m}^3$
- b) Void ratio, $e = 0.52$
- c) B-value, $B = 1.0$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1780 \text{ kg/m}^3$
- b) Void ratio, $e = 0.49$
- c) B-value, $B = 0.71$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.90 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$

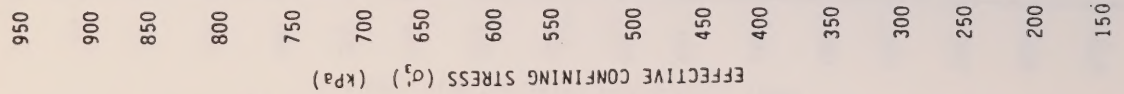
$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 2131.36 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 1263.16 \text{ kPa}$$

- b) At maximum σ_1/σ_3

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 1168.6 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 736.6 \text{ kPa}$$



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 27

AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 16

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
A110) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to

Consolidation

- a) Dry density, γ_{dry} = 1560 kg/m³
- b) Void ratio, e = 0.70
- c) B-value, B = 1.0

2) After Consolidation

- a) Dry density, γ_{dry} = 1640 kg/m³
- b) Void ratio, e = 0.62
- c) B-value, B = 0.77

3) Test Conditions

- a) Specimen size = 3.74x7.89 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = \text{nil}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = \text{nil}$$

- b) At maximum σ_1/σ_3

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 946.23 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 538.34 \text{ kPa}$$

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

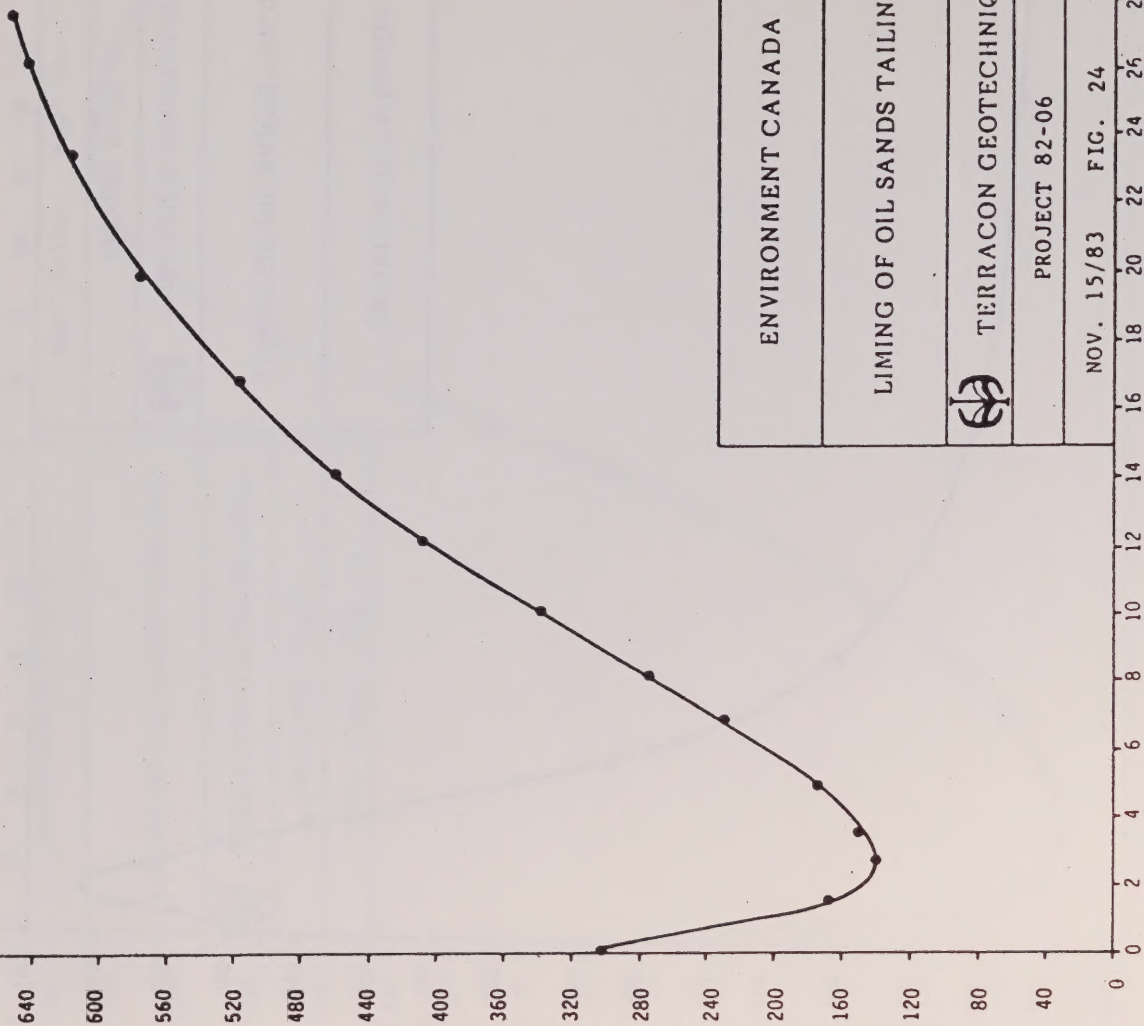


TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 24

AXIAL STRAIN, %



EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 21

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
A110) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, $\gamma_{dry} = 1700 \text{ kg/m}^3$
- b) Void ratio, $e = 0.56$
- c) B-value, $B = 0.97$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1740 \text{ kg/m}^3$
- b) Void ratio, $e = 0.53$
- c) B-value, $B = 0.50$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.86 \text{ cm}^3$
- b) Back pressure = 500 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 1957.64 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 1124.64 \text{ kPa}$
- b) At maximum σ_1/σ_3
 - $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 1376.12 \text{ kPa}$
 - $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 842.83 \text{ kPa}$

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

920

880

840

800

760

720

680

640

600

560

520

480

440

400

360

320

280

0

2

4

6

8

10

12

14

16

18

20

22

24

26

28

30

AXIAL STRAIN, %

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 29

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 18

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
Al10) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, $\gamma_{dry} = 1710 \text{ kg/m}^3$
- b) Void ratio, $e = 0.55$
- c) B-value, $B = 0.99$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1740 \text{ kg/m}^3$
- b) Void ratio, $e = 0.53$
- c) B-value, $B = 0.86$

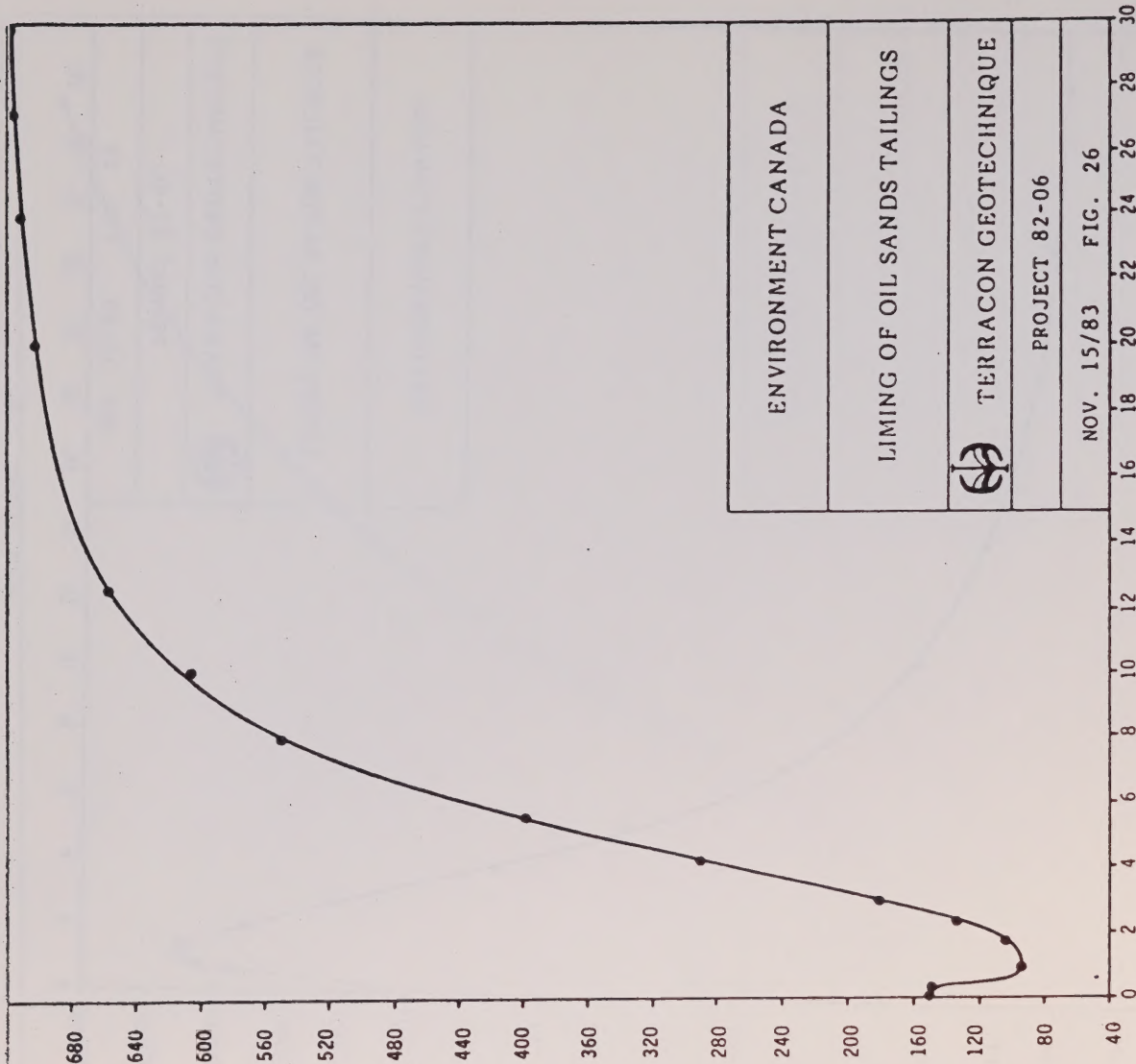
3) Test Conditions

- a) Specimen size = $3.74 \times 7.87 \text{ kg/m}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 753.96 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 464.58 \text{ kPa}$

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



AXIAL STRAIN, %

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 26

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 23

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83321 / 83225 (Flume Tank 11)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to

Consolidation

- a) Dry density, $\gamma_{dry} = 1740 \text{ kg/m}^3$
- b) Void ratio, $e = 0.53$
- c) B-value, $B = 1.0$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1770 \text{ kg/m}^3$
- b) Void ratio, $e = 0.50$
- c) B-value, $B = 0.78$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.87 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

a) At maximum $\sigma_1 - \sigma_3$

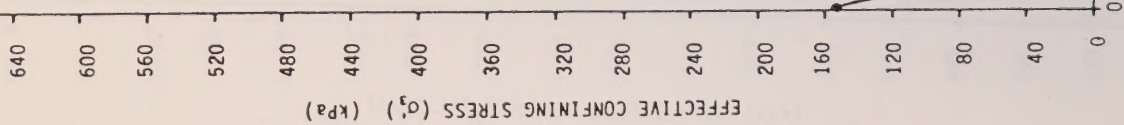
$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) = 1389.96 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_2) = 772.62 \text{ kPa}$$

b) At maximum σ_1/σ_3

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) = 511.90 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_2) = 310.02 \text{ kPa}$$



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 31

AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 20

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83610 (Flume Tank 3)

Sample Treatment: a) lime (CaO) = 0.9 gm/litre
b) polymer (Cyanamid,
Allio) = 8 mg/litre

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to

Consolidation

- a) Dry density, $\gamma_{dry} = 1670 \text{ kg/m}^3$
- b) Void ratio, $e = 0.60$
- c) B-value, $B = 1.0$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1680 \text{ kg/m}^3$
- b) Void ratio, $e = 0.58$
- c) B-value, $B = 0.92$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.89 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

a) At maximum $\sigma_1 - \sigma_3$

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 1117.05 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 620.97 \text{ kPa}$$

b) At maximum σ_1/σ_3

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 395.41 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 242.45 \text{ kPa}$$

640

600

560

520

480

440

400

360

320

280

240

200

160

120

80

0

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

0

2

4

6

8

10

12

14

16

18

20

22

24

26

28

30

AXIAL STRAIN, %

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 28

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 25

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83321 / 83225 (Flume Tank 11)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, $\gamma_{dry} = 1750 \text{ kg/m}^3$
- b) Void ratio, $e = 0.52$
- c) B-value, $B = 0.95$

2) After Consolidation

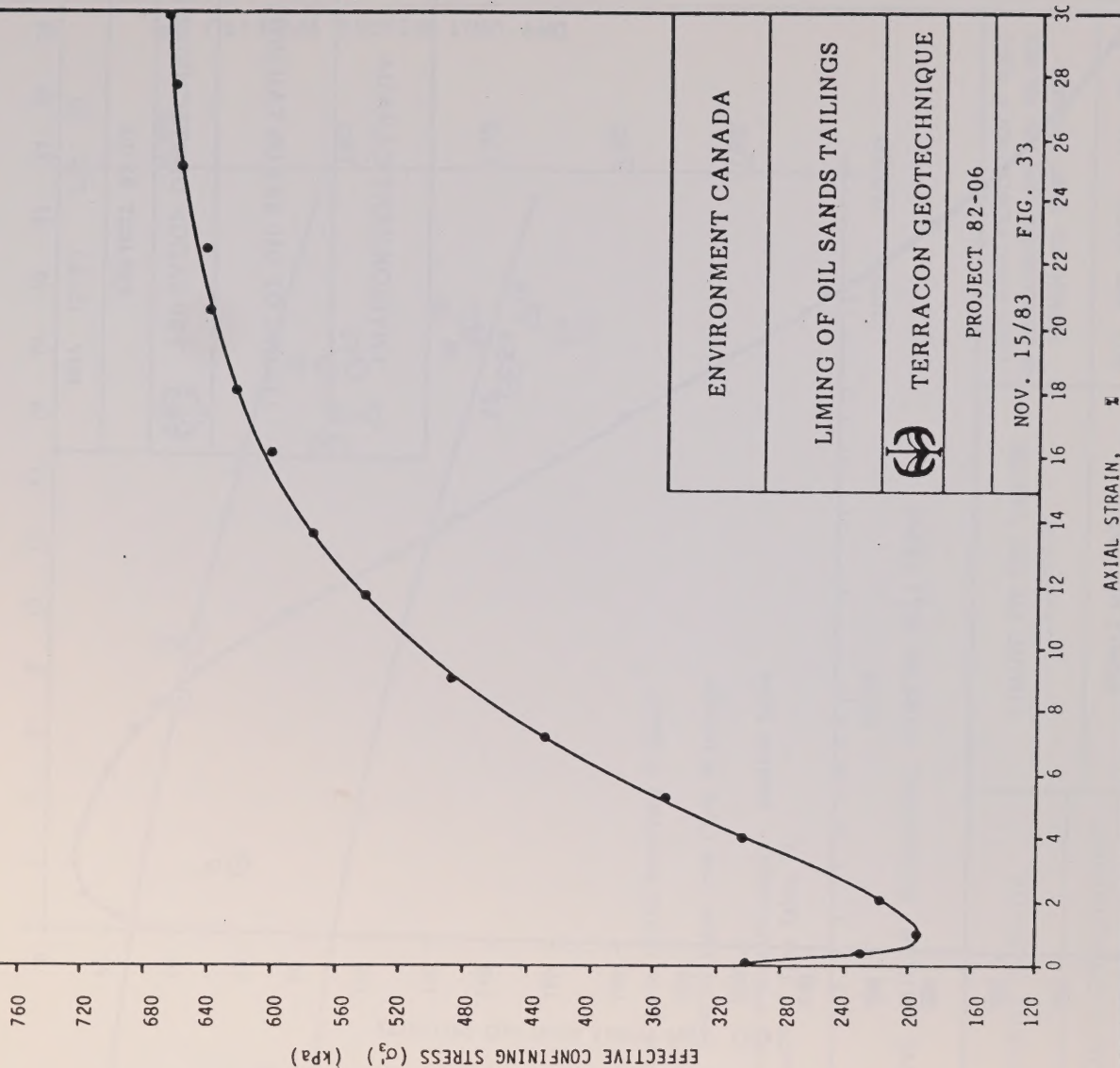
- a) Dry density, $\gamma_{dry} = 1780 \text{ kg/m}^3$
- b) Void ratio, $e = 0.50$
- c) B-value, $B = 0.56$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.89 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 1471.75 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 828.22 \text{ kPa}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 758.47 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 453.93 \text{ kPa}$



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 33

AXIAL STRAIN, %

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 22

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810(1) & (2)(Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, $\gamma_{dry} = 1650 \text{ kg/m}^3$
- b) Void ratio, $e = 0.61$
- c) B-value, $B = 1.0$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1670 \text{ kg/m}^3$
- b) Void ratio, $e = 0.60$
- c) B-value, $B = 0.93$

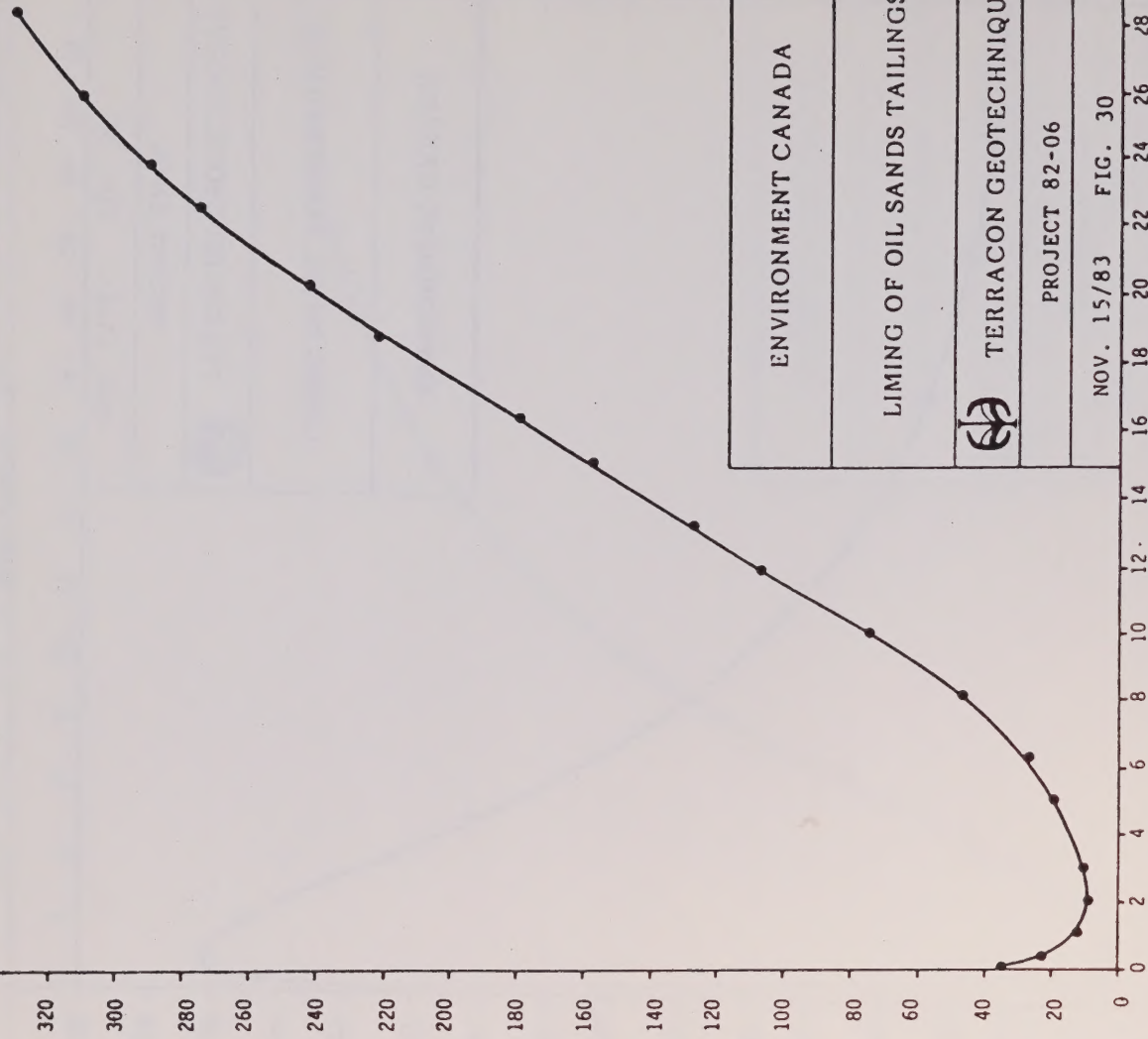
3) Test Conditions

- a) Specimen size = $3.74 \times 7.87 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 53.63 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 31.58 \text{ kPa}$

EFFECTIVE CONFINING STRESS (σ_3) (kPa)



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS

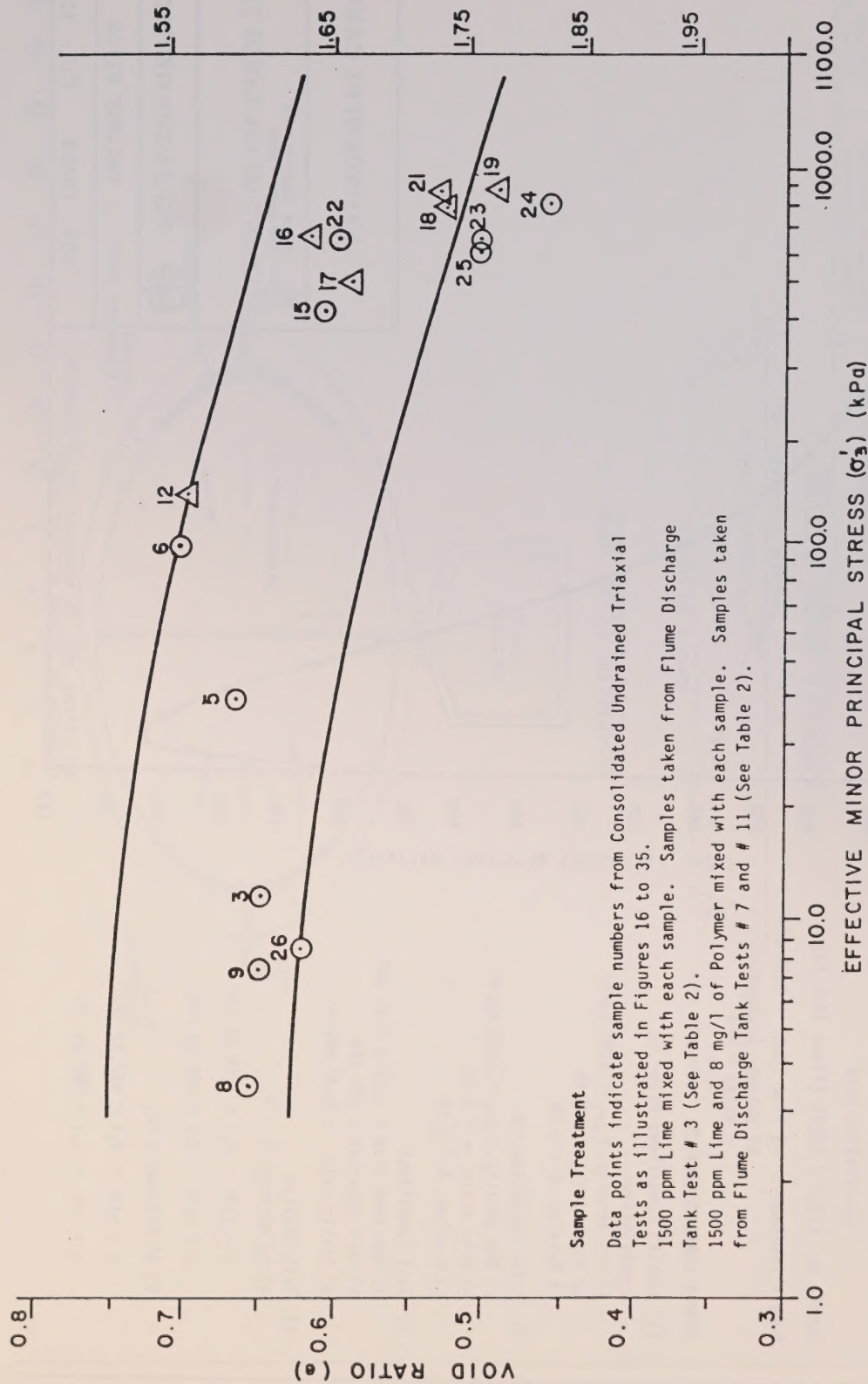


TERRACON GEOTECHNIQUE

PROJECT 82-06

NOV. 15/83 FIG. 30

AXIAL STRAIN, %



Sample Treatment

Data points indicate sample numbers from Consolidated Undrained Triaxial Tests as illustrated in Figures 16 to 35.
 1500 ppm Lime mixed with each sample. Samples taken from Flume Discharge Tank Test # 3 (See Table 2).
 1500 ppm Lime and 8 mg/l of Polymer mixed with each sample. Samples taken from Flume Discharge Tank Tests # 7 and # 11 (See Table 2).

DRY UNIT WEIGHT (γ_d) (T / m³)

 ENVIRONMENT CANADA	LIMING OF OIL SANDS TAILINGS	STEADY STATE POINTS FROM R TESTS ON CONSOLIDATED LIME AND POLYMER TREATED OIL SANDS TAILINGS
	PROJECT NO. 82-06	DATE NOV. 23/83 FIG. NO. 35

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 24

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83321 / 83225 (Flume Tank 11)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
A110) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to
Consolidation

- a) Dry density, $\gamma_{dry} = 1790 \text{ kg/m}^3$
- b) Void ratio, $e = 0.49$
- c) B-value, $B = 0.98$

2) After Consolidation

- a) Dry density, $\gamma_{dry} = 1820 \text{ kg/m}^3$
- b) Void ratio, $e = 0.46$
- c) B-value, $B = 0.59$

3) Test Conditions

- a) Specimen size = $3.74 \times 7.87 \text{ cm}^3$
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$

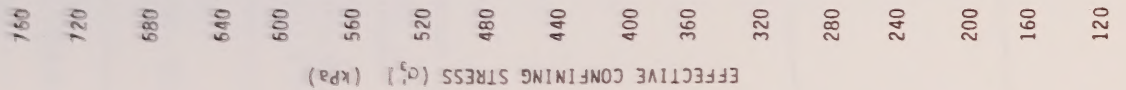
$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 1668.02 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 908.68 \text{ kPa}$$

- b) At maximum σ_1/σ_3

$$p = \frac{1}{3}(\sigma_1 + \sigma_3) = 927.43 \text{ kPa}$$

$$q = \frac{1}{3}(\sigma_1 - \sigma_3) = 580.86 \text{ kPa}$$



ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



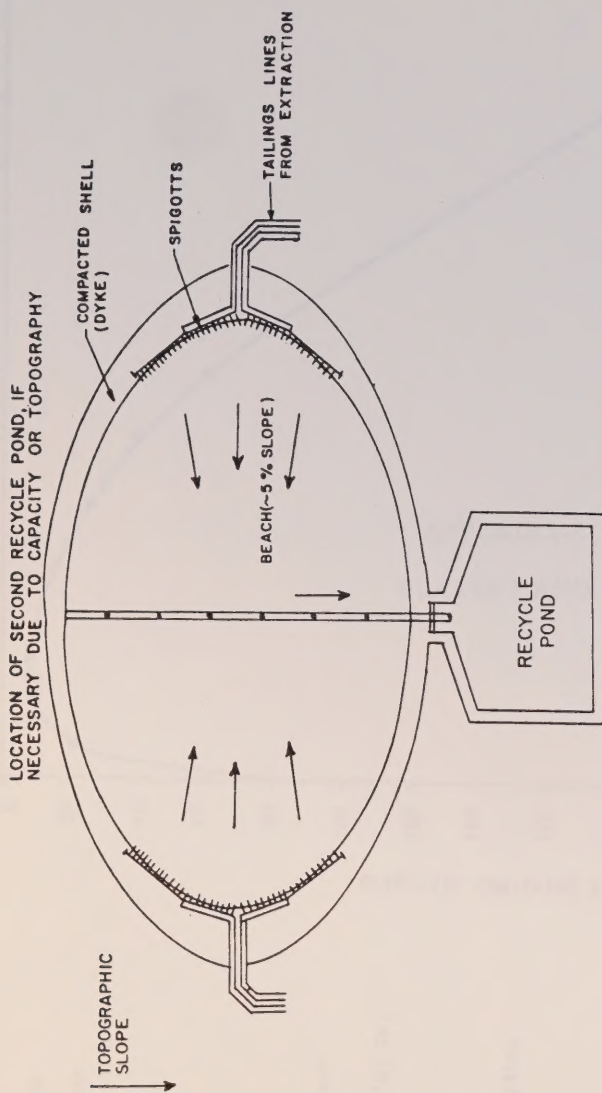
TERRACON GEOTECHNIQUE

PROJECT 82-06

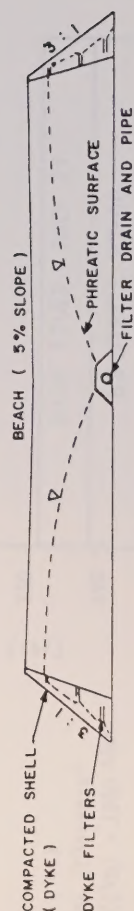
NOV. 15/83

FIG. 32

AXIAL STRAIN, %



SCHEMATIC PLAN VIEW



SCHEMATIC CROSS SECTION

ENVIRONMENT CANADA	LIMING AND POLYMER ADDITION TO WHOLE OIL SAND TAILINGS	CONCEPTUAL DISPOSAL DESIGN: SINGLE STACK WITH SPIGOTTED BEACHES AND FILTER DRAINS
TERRACON GEOTECHNIQUE	PROJECT 82-06	DATE Mar. 23/84 Fig. No. 37

EFFECTIVE CONFINING STRESS BEHAVIOUR AS A FUNCTION OF AXIAL STRAIN

Test No: 26

Test Type: Isotropically consolidated
undrained triaxial
compression test

Sample No: 83428A810(1) & (2) (Flume Tank 7)

Sample Treatment: a) lime (CaO) = 1500 ppm
b) polymer (Cyanamid,
Al10) = nil

SAMPLE CHARACTERISTICS

1) Initial Conditions Prior to Consolidation

- a) Dry density, γ_{dry} = 1630 kg/m³
- b) Void ratio, e = 0.65
- c) B-value, B = 0.96

2) After Consolidation

- a) Dry density, γ_{dry} = 1640 kg/m³
- b) Void ratio, e = 0.62
- c) B-value, B = 0.86

3) Test Conditions

- a) Specimen size = 3.74 x 7.87 cm³
- b) Back pressure = 600 kPa
- c) Strain rate = 0.30 mm/min

4) Test Results

- a) At maximum $\sigma_1 - \sigma_3$
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = \text{nil}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = \text{nil}$
- b) At maximum σ_1/σ_3
 $p = \frac{1}{2}(\sigma_1 + \sigma_3) = 168.32 \text{ kPa}$
 $q = \frac{1}{2}(\sigma_1 - \sigma_3) = 107.0 \text{ kPa}$

ENVIRONMENT CANADA

LIMING OF OIL SANDS TAILINGS



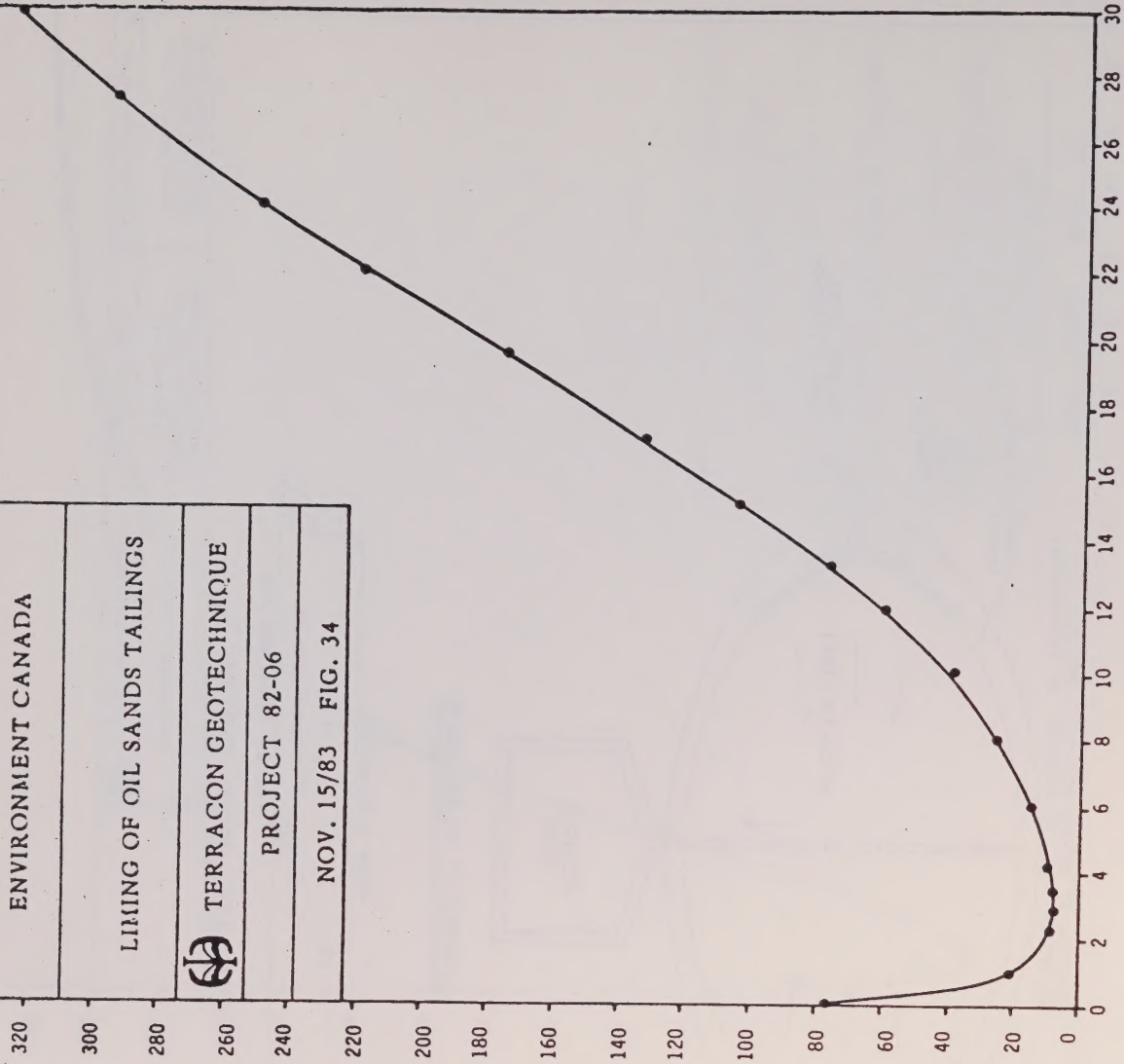
TERRACON GEOTECHNIQUE

PROJECT 82-06

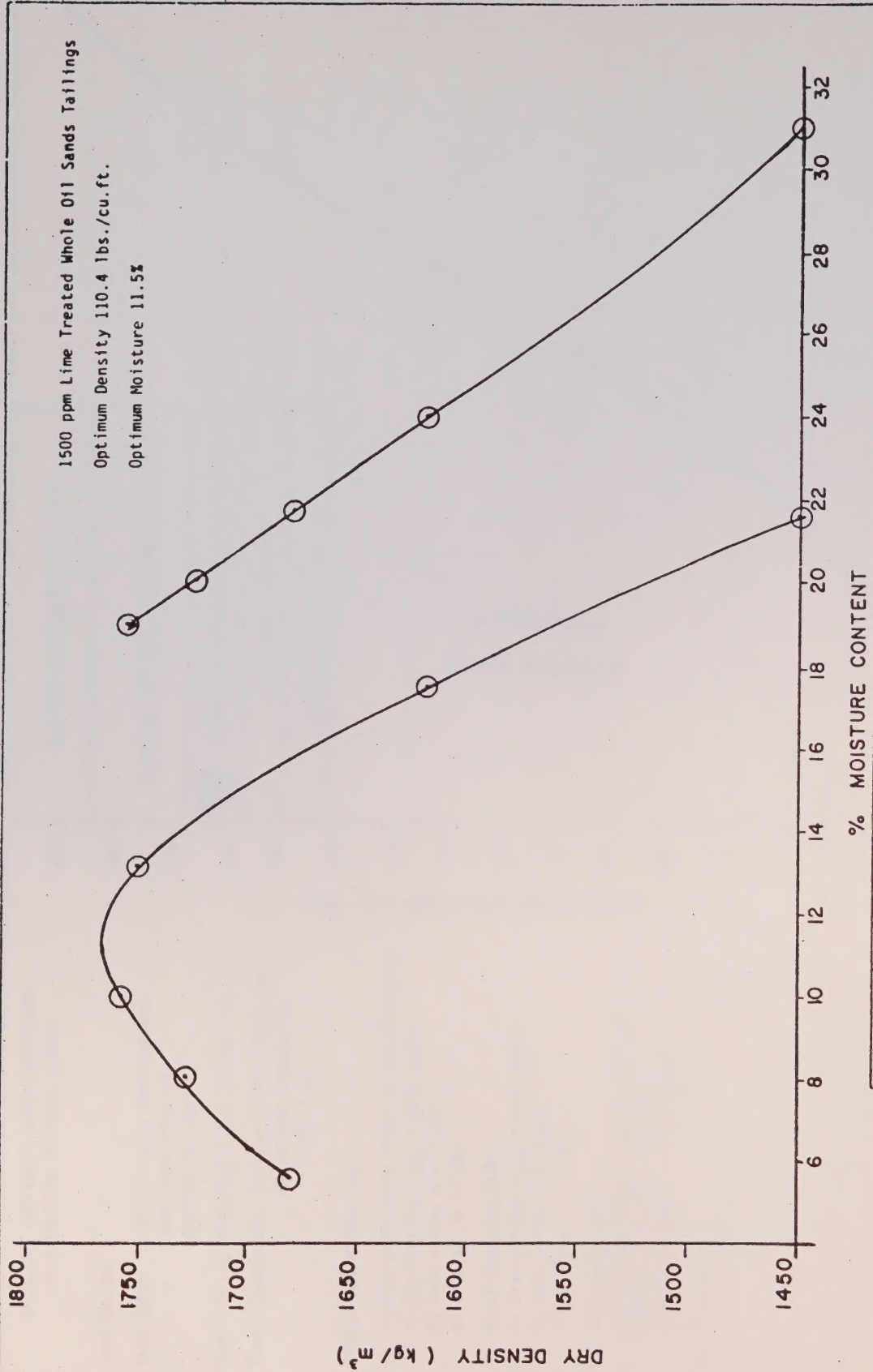
NOV. 15/83 FIG. 34

EFFECTIVE CONFINING STRESS (σ_3) (kPa)

AXIAL STRAIN, %



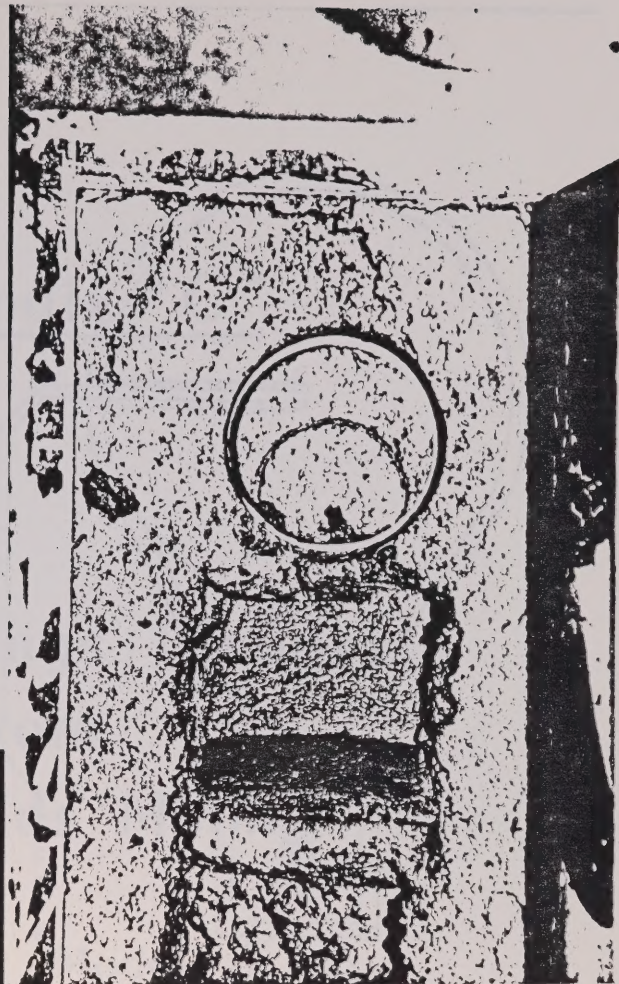
APPENDIX C
PLATES 1 AND 2



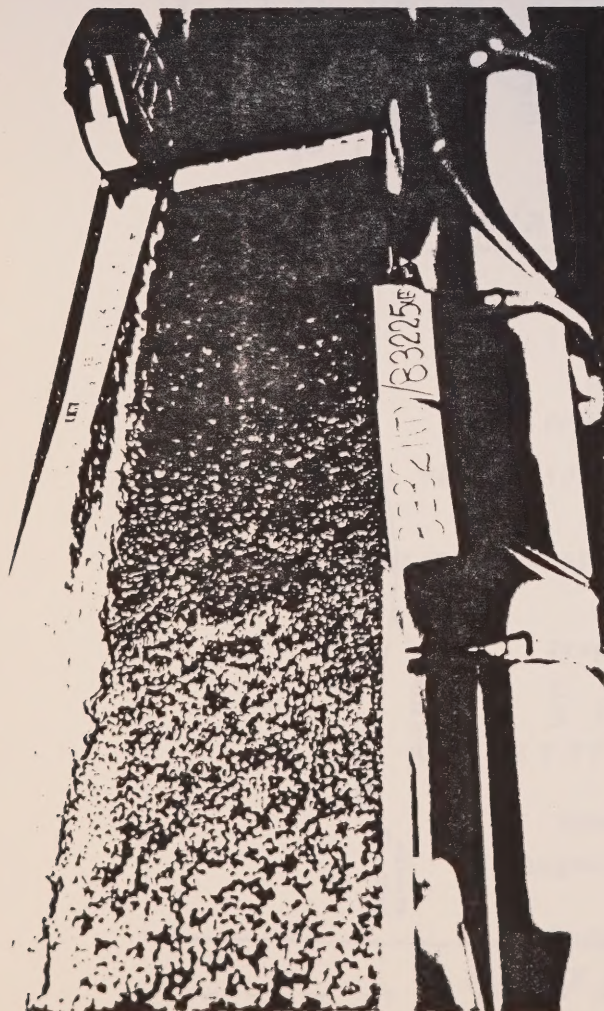
 ENVIRONMENT CANADA TERRACON GEOTECHNIQUE	LIME OF OIL SANDS TAILINGS	STANDARD PROCTOR COMPACTION TEST 1500 ppm Whole Tailings	Figure No. 36

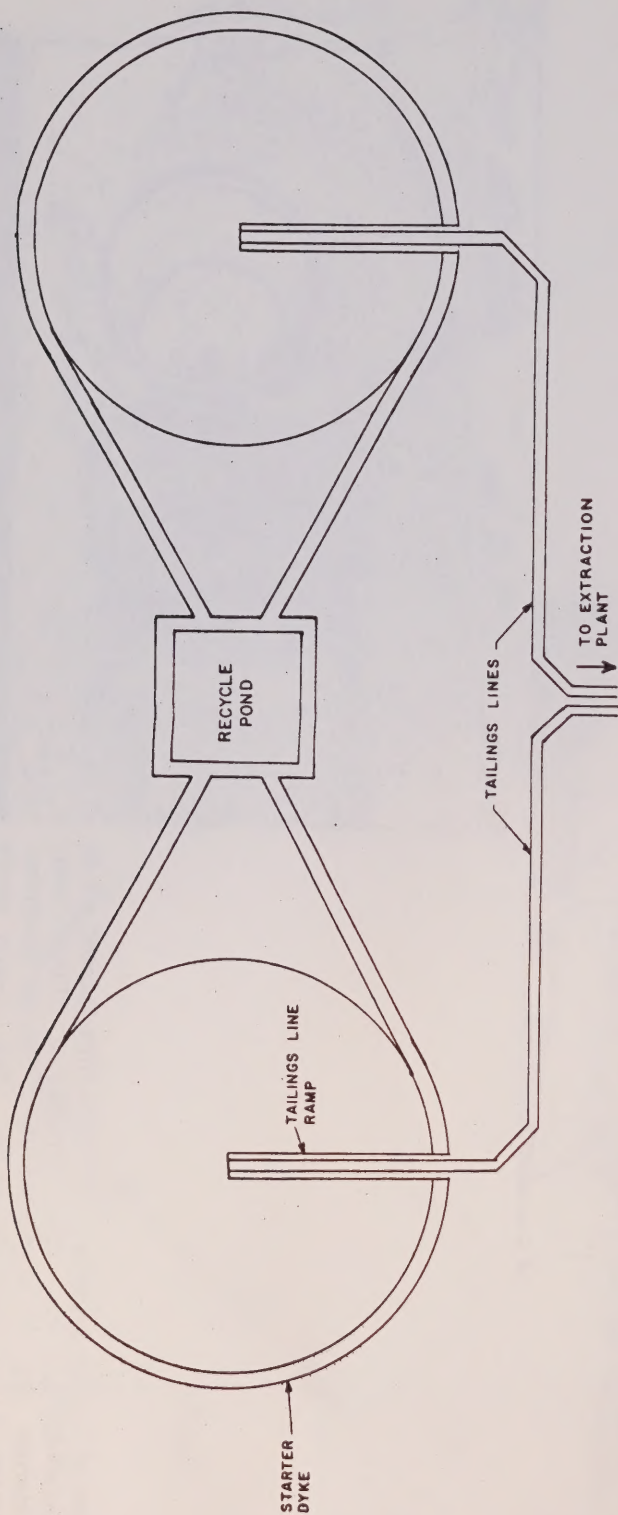
PLATE I

Top view of typical Flume Tank Test showing sample 8321. Sample 83225, a second layer, lies beneath 83 and is not visible. Tank width is approximately 15 cm. Note apparent uniformity of sample.

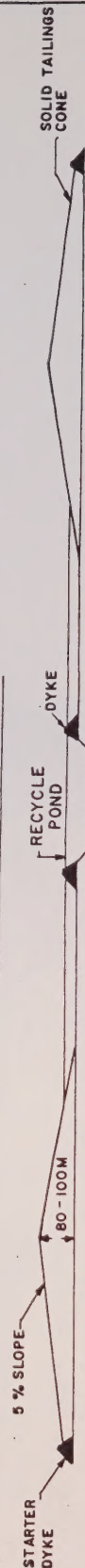


Top view of freshly deposited 1500 ppm lime treated whole oil sands tailings in upper portion of flume tank. Consolidation ring is approximately 7 cm in diameter. Tank width is approximately 15 cm. View clearly shows the paste-like consistency of the tailings within a few hours of deposition. Note uniformity of sample.





SCHEMATIC PLAN VIEW



SCHEMATIC CROSS-SECTION

 TERRACON GEOTECHNIQUE	ENVIRONMENT CANADA	LIMING AND POLYMER ADDITION TO WHOLE OIL SANDS TAILINGS PROJECT 82-06	CONCEPTUAL DISPOSAL DESIGN: DOUBLE STACK WITH RECYCLE POND
		DATE Mar. 23/84 Fig. No. 38	

Appendix "C"

"Dry" Tailings Disposal from Oil Sands Mining

Water Model

Prepared For

ENVIRONMENTAL PROTECTION SERVICE, ENVIRONMENT CANADA
AND
DEPARTMENT OF SUPPLY AND SERVICES CANADA

Prepared By:

C. J. Lee
S. J. Lane
C-H SYN FUELS LTD.

Submitted:

August, 1984

Contract No:

52SS KE 145-2-0439

TABLE OF CONTENTS

APPENDIX C

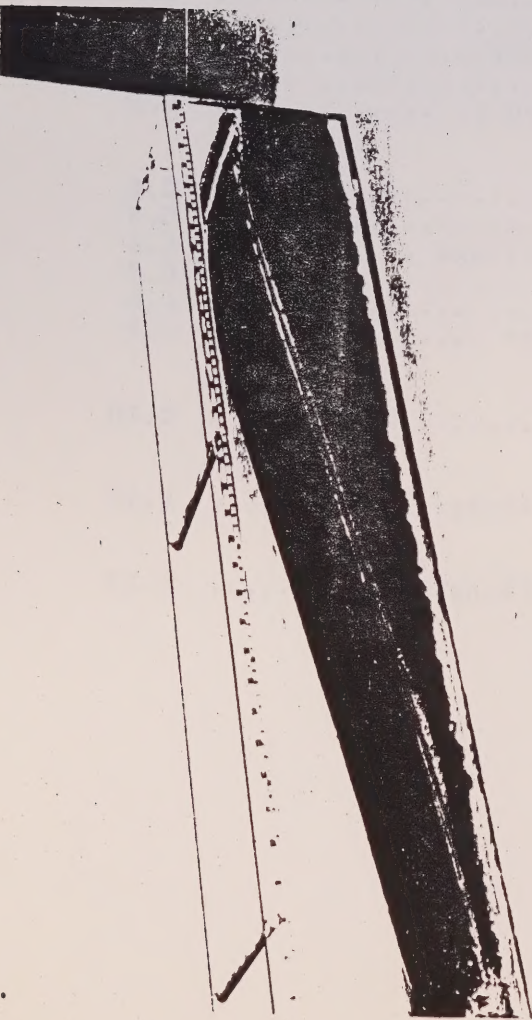
	<u>PAGE</u>
C.1 INTRODUCTION	C.1
C.2 BASIC ASSUMPTIONS	C.1
C.2.1 Oil Sand Feed Conditions	C.1
C.2.2 Extraction Conditions	C.2
C.2.3 Tailings Pond Input/Output Assumptions	C.2
C.2.4 Tailings Pond Material Balance	C.3
C.3 MATERIAL BALANCE CONCEPTS	C.3
C.3.1 Approach	C.3
C.3.2 Total Tailings Water Composition	C.4
C.3.3 Tailings Pond Water Balance	C.4
C.3.4 Tailings Pond Water Composition	C.5
C.4 LIME TREATMENT SCHEME	C.5
C.4.1 Assumptions	C.5
C.4.2 Calcium Balance in Treated Tailings	C.6
C.4.3 Bicarbonate (HCO_3^-) Balance	C.7
C.4.4 Sodium (Na^+) Balance	C.8
C.4.5 Water Model With Lime Treatment	C.9
C.5 RESULTS AND DISCUSSIONS	C.10
Table C.1 Tailings Pond Water Modelling	C.12
(without Treatment)	
Table C.2 Tailings Pond Water Modelling	C.13
(with Lime Treatment)	

PLATE 2

Adjacent Photograph illustrates the typical layering and slope formation of untreated tails. Fines content of run-off water amounts to 7% particulate material.



Adjacent Photograph illustrates typical full flume length with lime treated whole oil sand tailings deposited in a typical sequence. Two sequences of deposition are shown.



APPENDIX C - TAILINGS POND WATER MODELLING

C.1 INTRODUCTION

Modelling of the tailings pond water material balance is primarily based on Syncrude's ongoing operations. This includes many factors such as oil sand feed throughput, oil sand composition, water requirements, extraction conditions, pond water recycle, mine drainage and tailings pond properties. This approach, based on our understanding of what happens at Syncrude should be reasonably appropriate for a new plant.

This modelling employs a micro-computer "spread-sheet" type program "Report Manager", which provides the essential flexibility and predictive capability for the complicated calculations of many time-dependent contaminant variables. This model, can also be conveniently modified to assess the water related effects of the lime/polymer tailings treatment scheme. It has been used primarily to predict contaminant buildup and reactions that affect or are affected by the presence of lime.

C.2 BASIC ASSUMPTIONS

C.2.1 Oil Sand Feed Conditions (all of which are independently variable):

- Oil sand composition : bitumen (11.5% by wt.), H₂O (4.4%), fines (<44 um, 12.4%), sand (71.7%).

(C.3)

- 30% of the water in the total tailings stream is eventually trapped in sand and sludge voids and, therefore, not available for recycle.

C.2.4 Tailings Pond Material Balance:

- The average composition of tailings pond water (upper 10 m, recyclable quality) in 1980 : Na^+ (280 ppm), Cl^- (75 ppm), $\text{SO}_4^{=}$ (190 ppm), HCO_3^- (470 ppm), organic acids (36 ppm).
- Mine drainage water composition : Na^+ (680 ppm), Cl^- (900 ppm), $\text{SO}_4^{=}$ (25 ppm), HCO_3^- (380 ppm), organic acids (5 ppm).
- When the total tailings stream is discharged to the pond, a considerable degree of mixing is expected to take place. It is therefore assumed that of the 30% tailings water trapped in sand and sludge layers, half of it (15%) is available for mixing.
- 70% of TOC in tailings pond water is assumed to be non-volatile organic acids.

C.3 MATERIAL BALANCE CONCEPTS

C.3.1 Approach:

- The measured physical and chemical properties of Syncrude's tailings pond in 1980 (MacKinnon, 1981) are used as the base data for the modelling.
- For each subsequent year, the concentrations of specific

(C.5)

- The general format for pond water balance in any year is:

Pond water balance (V)

= Pond water volume of previous year - Water recycled

+ Precipitation - Evaporation + Mine drainage

+ Total tailings water less water trapped in sand/sludge

where precipitation = evaporation.

C.3.4 Tailings Pond Water Composition:

- The general equation for calculating the concentration of a particular parameter (C_I) in any year is:

Mass in pond water ($C_I * V$)

= Mass in pond water of previous year

- Mass in recycled pond water

+ Mass in mine drainage water input

+ Mass in total tailings water input less mass trapped in bottom sand/sludge

where mass = mass of parameter I,

recycled pond water = pond water of previous

year quality.

- The modelling results are presented in Table C.1.

C.4 LIME TREATMENT SCHEME

C.4.1 Assumptions:

- The composition of total tailings (slurry): Water : Sand:

(C.2)

- Connate water composition : Na^+ (800 ppm), Cl^- (1140 ppm), $\text{SO}_4^{=}$ (30 ppm), HCO_3^- (550 ppm).
- Fresh make-up water composition : Na^+ (12 ppm), Cl^- (10 ppm), $\text{SO}_4^{=}$ (25 ppm), HCO_3^- (110 ppm).

C.2.2 Extraction Conditions (usually varied as a function of oil sand feed grade)

- Caustic (NaOH) consumption : 0.020 to 0.025% by wt. of oil sand throughput.
- Water requirements: 80% by wt. of oil sand throughput.

C.2.3 Tailings Pond Input/Output Assumptions:

- Recycle from tailings pond (starting in 1980) is approximately 65% of the water requirements.
- Precipitation input is balanced by evaporation output.
- Process water input comes from tailings streams (including extraction and froth treatment) only, the direct input from other plants is either zero or insignificant.
- Mine drainage water (mine depressurization water diluted by surface runoff) input started in 1983 at a rate of $1.5 \times 10^6 \text{ m}^3/\text{yr}$. The rate is assumed to increase to $4.0 \times 10^6 \text{ m}^3/\text{yr}$ in 1984 and to $5.4 \times 10^6 \text{ m}^3/\text{yr}$ in 1985 and thereafter.
- The volume of "free" pond water available for "effective" mixing on a long term year-round basis (and acceptable as potential reclaim water in terms of solid content) in 1980 was approximately $110 \times 10^6 \text{ m}^3$.

test data, Appendix A) in the raw tailings water, the calculated removal of Ca^{++} by CaCO_3 precipitation (with lime addition) is 480 ppm. The residual concentrations of HCO_3^- and $\text{CO}_3^{=}$ are estimated at 1 and 5 ppm levels respectively.

- Removal of Ca^{++} by clay mineral cation exchange : The CEC of kaolinite and illite clays in total tailings is estimated at 5.1 meq/1000 g of tailings. This is equivalent to approximately 200 mg/l (or ppm) of Ca^{++} exchange capacity on the tailings water basis.
- Test data from Zenon show that at the 800 mg/l CaO dosage level, the residual Ca^{++} in treated tailings water is virtually the same as in raw tailings. This indicates that a total of 100 ppm Ca^{++} removal is not accounted for by either CaCO_3 precipitation or clay CEC. This balance is probably due to either a higher CEC of clays than assumed earlier and/or other removal processes such as organo-metallic precipitation of calcium soaps.

C.4.3 Bicarbonate (HCO_3^-) Balance:

- The material balance for inorganic carbonates, including both HCO_3^- and $\text{CO}_3^{=}$, is most important in the water modelling of the lime treatment scheme.
- At the tailings pond's prevailing pH of 8.2, in excess of 99% of inorganic carbonate is present as HCO_3^- . On the other hand, when the raw tailings is treated with 800 mg/l lime

(C.4)

parameters in the total tailings stream are first calculated, in terms of mg per liter of tailings water (or ppm), based on material balance from connate water, recycle water, fresh makeup water, and any process input sources. No chemical reactions or physical adsorption of significance are expected to affect the mass balances of the parameters indicated.

- This total tailings water of known composition is then allowed to mix with existing "free" pond water (of previous year) as well as the mine drainage stream (of the same year), resulting in pond water of average composition for that particular year.

C.3.2 Total Tailings Water Composition:

- The general format for a particular parameter (e.g. parameter "I") in any year is:

Mass rate in total tailings water

= Mass rate from connate water +

Mass rate from recycle water +

Mass rate from fresh makeup water +

Mass rate(s) from process source(s)

where

mass rate = mass rate of parameter I;

recycle water = pond water of previous year quality.

C.3.3 Tailings Pond Water Balance:

- The pond water modelled is the "free" pond water available for mixing only.
- Pond water volume in 1980 = $110 \times 10^6 \text{ m}^3$.

consumption, the connate and recycle waters, but also the cation exchange mechanism of oil sand clay minerals.

- The cation exchange capacities of clay minerals may result in the release of Na^+ , adding as much as 230 ppm of Na^+ to the treated water (assuming stoichiometric reactions which may or may not be the case).

C.4.5 Water Model With Lime Treatment:

- The water model for Syncrude type operations in Table C.1 can be readily modified to reflect the effects of a chemical treatment process using lime and polymer.
- The lime treatment of whole tailings greatly facilitates the settling of fines and produces a far more consolidated sludge in the sand-clay product than Syncrude's existing disposal process. It not only speeds up the recycle water generation process, but also frees an extra amount of recyclable water that would otherwise be "permanently" trapped in the interstices of sludge fines and sand.
- The overall effect is, therefore, to allow for a higher percentage (e.g., 80-90%) of available recycle water and to reflect changes resulting from chemical interactions of the lime (e.g., HCO_3^-).
- Table C.2 presents the results of lime treatment modelling where 80% water recycle and chemical treatment starting in 1988 (corresponding to mine backfill operations) have been assumed.

(C.6)

residual bitumen = 50 : 50 : 1.2.

- The specific gravity of total tailings is about 1.45.
- Lime dosage = 800 mg CaO/l of total tailings
= 550 ppm CaO by wt. of total tailings
= 780 ppm Ca^{++} by wt. of tailings water.
- Clay minerals in oil sand:
kaolinite = 65% of clay = 32% of fines,
illite = 35% of clay = 17% of fines.
- Cation exchange capacity (CEC): kaolinite (5 meq/100g),
illite (30 meq/100 g).

C.4.2 Calcium Balance in Treated Tailings:

- In lime treatment of total tailings, the main Ca^{++} removal mechanisms include the chemical precipitation of CaCO_3 (not CaSO_4 due to its considerably higher solubility) and the cation exchange with clay minerals present in the tailings.
- Removal of Ca^{++} by CaCO_3 precipitation: With a lime dosage of 800 mg CaO/l of tailings (780 ppm Ca^{++} on tailings water basis), the pH of the total tailings water is expected to be at about 10.5 to 11.3. At this pH level, the majority of HCO_3^- is converted to CO_3^{--} which would then react quantitatively with available Ca^{++} to form CaCO_3 until the solubility product ($K_{sp} = 5 \times 10^{-9}$ in distilled water at 25°C ; a $K_{sp} = 5 \times 10^{-8}$ is estimated for tailings water at 10°C) limit is met.

Assuming a HCO_3^- concentration of 720 ppm (from Zenon's

recarbonation is used to adjust the pH of the treated water to 8.0 - 8.5, the HCO_3^- concentration in the recycle water may be expected at approximately 60-70 ppm. This low level of HCO_3^- in recycle water (compared with Syncrudes' actual level of about 650 ppm in 1982) will greatly reduce the HCO_3^- concentration in the raw extraction tailings. That will in turn result in the reduction of lime dosage requirement by as much as 240 mg/l.

dosage, a pH of approximately 11 and more than 80% of inorganic carbonate in the form of $\text{CO}_3^{=}$ result.

- In addition to the oil sand connate water, the recycle water and the fresh make-up water, the major sources of HCO_3^- in tailings water also include the absorption of atmospheric CO_2 into the alkaline solution during the conditioning and secondary recovery processes in the extraction plant. It is believed that this CO_2 absorption process alone might contribute as much as 400 ppm of the total HCO_3^- level in the raw tailings water.
- The input of HCO_3^- through the absorption of CO_2 over the tailings pond surface is not considered as a significant factor (mass transfer calculations yield estimates of less than 1 ppm) in the overall material balance.
- As stated previously, the addition of 800 mg/l of lime to total tailings will likely produce a treated tailings water with less than 10 ppm concentration of residual $\text{CO}_3^{=}$ and HCO_3^- . If the excess hydroxide alkalinity is to be removed by recarbonation before the treated water is recycled, the HCO_3^- concentration in the recarbonated water may be assumed at 65 ppm (corresponding to a reduction in pH from 11 to 8).

C.4.4 Sodium (Na^+) Balance:

- In lime treatment of total tailings the main sources of Na^+ in treated tailings water include not only the NaOH

SAVINGS DISPOSAL MATERIAL BALANCE

NOTES: 1. The assumed composition for mine drainage water is: Na+ (680ppm), Cl- (930ppm), HCO3- (380ppm), SO4= (25ppm), Organic acids (5ppm).

2. Approximately 70% of TOC in tailings pond water is assumed to be non-volatile (C15 to C30) organic acids.

C.5 RESULTS AND DISCUSSIONS

- A period of 31 years (from 1980 to 2010) is included in the model to cover the design life of Syncrude's operations.
- The oil sand throughput data is based on the original design and does not currently allow for expansion beyond the 129,000 B/D expected production rate.
- The model is very flexible and can readily be used to analyze any changes in value of variables such as pond water recycle rate, connate water composition, mine drainage flow and concentrations, etc. which might be desired.
- With all the assumptions needed to develop the model, the results in Table C.1 do not always agree with Syncrude's report (MacKinnon, 1981). For a particular parameter, it is always possible to have certain significant process input/output factors which have not been accounted for in the calculations. These may include chemical additions from process operations or chemical reactions such as organo-metallic precipitation and complexation. Physical phenomena such as ion exchange, adsorption/desorption, air-water interaction (e.g. CO₂ equilibrium) and other processes may also result in differences between predicted and measured concentrations. At any rate, empirical adjustments have been made such that the modelling results are more or less in agreement with Syncrude's observed concentrations.
- If lime treatment for tailings disposal can be employed by a Syncrude-type operation from the very beginning, and if

Appendix "D"

"Dry" Tailings Disposal from Oil Sands Mining

Bibliography

Prepared for:

ENVIRONMENTAL PROTECTION SERVICE, ENVIRONMENT CANADA
and
DEPARTMENT OF SUPPLY AND SERVICES CANADA

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C-H SYN FUELS LTD.

Submitted:

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Contract No:

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